University of Alberta

Economic Analysis of Carbon Sequestration on Public Forest Lands

by

Tanya Corinne Maynes

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment

of the

requirements for the degree Masters of Science

in

Forest Economics

Department of Rural Economy

Edmonton, Alberta

Spring 2003

National Library of Canada
Acquisitions and Bibliographic Services
395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale du Canada
Acquisitions et services bibliographiques
395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-82307-5

Canada

University of Alberta

Library Release Form

Name of Author: Tanya Corinne Maynes

Title of Thesis: Economic Analysis of Carbon Sequestration on Public Forest Lands

Degree: Masters of Science

Year this Degree Granted: 2003

Permission is hereby granted to the University of Alberta Library to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves all other publication and other rights in association with the copyright in the thesis, and except as herein before provided, neither the thesis nor any substantial portion thereof may be printed or otherwise reproduced in any material form whatever without the author's prior written permission.

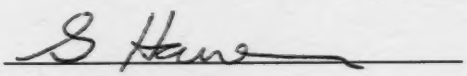
#305-55 Akins Drive
St. Albert, AB
T8N-3M6

Date: January 31, 2003

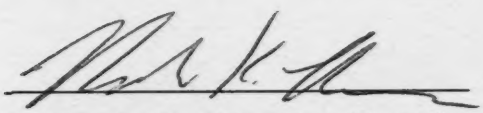
University of Alberta

Faculty of Graduate Studies and Research

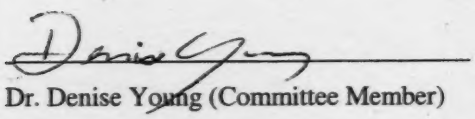
The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Economic Analysis of Carbon Sequestration on Public Forest Lands" submitted by Tanya Corinne Maynes in partial fulfillment of the requirements for the degree of Masters of Science in Forest Economics.



Dr. Grant Hauer (Supervisor)
Rural Economy



Dr. Marty Luckert (Committee Member)
Rural Economy



Dr. Denise Young (Committee Member)
Department of Economics

Date: January 31, 2003

ABSTRACT

This study investigates the effects of possible carbon accounting stances on forest management, where a carbon accounting stance is defined as a collection of carbon pools that have incentives placed on them. The purpose of this study is twofold. The first objective is to examine how forest management changes when a forestry firm is faced with incentives to sequester carbon. The second objective is to estimate carbon supply and carbon credit supply curves for the firm under alternative carbon accounting stances. The approach was to construct a linear programming model of a forest products firm operating on a Forest Management Agreement Area in Northern Alberta. Various modeling configurations were included to examine the effects of changes in carbon prices and carbon accounting stance. The results are used to suggest important design issues and identify policy risks in associated with invoking article 3.4 of the Kyoto Protocol.

Acknowledgement

I would like to thank Dr. Hauer for his patience and guidance in helping me to complete what seemed at times like an insurmountable task. I would also like to thank my committee members, Dr. Young and Dr. Luckert, for their invaluable comments, which were vital in the development of this thesis.

I would like to thank the dedicated staff in the Department of Rural Economy for their help and support throughout my years in the Department. I would also like to extend my gratitude to the many friends I made while in the Department. You helped make graduate studies not only bearable but enjoyable. A special thank you go to Jamie, Roy, Chanchoura, Nancy and Jenn – your friendship is much appreciated.

I would like to thank my family for without your support this would not have been possible.

Finally, I would like to extend a big hug and thank you to my husband Bryce. Without your love, patience and support, completion of this thesis would not be possible. Knowing you were behind me every step of the way made this journey possible.

Table of Contents

CHAPTER 1: INTRODUCTION 1

1.1 INTRODUCTION 1
1.2 GENERAL PROBLEM AND PREVIOUS RESEARCH 3
1.3 RESEARCH OBJECTIVES 6
1.4 THESIS STRUCTURE 7

CHAPTER 2: BACKGROUND 8

2.1 SEQUESTERING CARBON WITH FORESTS: BIOLOGICAL AND PHYSICAL ASPECTS 8
The Forest Carbon Cycle 9
Stand Level Carbon Dynamics 10
2.2 MANIPULATION OF CARBON STOCKS 13
Forest Level Carbon Dynamics 16
2.3 ECONOMICS OF CARBON SEQUESTRATION 19
2.4 POLICY ISSUES 22
2.5 SUMMARY 27

CHAPTER 3: A FOREST MANAGEMENT SCHEDULING MODEL WITH AN INTEGRATED CARBON BUDGET MODEL 28

3.1 MODEL FORMULATION 28
3.2 SUMMARY 38

CHAPTER 4: MODEL CALIBRATION 39

4.1 DATA AND CALIBRATION 39
Model Assumptions 40
4.2 YIELD CURVE CONSTRUCTION 46
Weldwood Data 46
4.3 YIELD CURVES DETAILS 50
4.3.1 Fire Origin Yield Curves 50
4.3.2 Extensive Yield Curves 51
4.3.3 Basic Yield Curves 51
4.3.4 Intensive Management Yield Curves 54
4.4 THE CANADIAN FOREST CARBON BUDGET MODEL 54
4.4.1 Introduction to the Carbon Budget Model of the Canadian Forest Sector 55

4.4.2 Carbon Budget Model Simulations *57*
4.4.3 Carbon Budget Model Simulation Methods *58*
4.5 SUMMARY 62

CHAPTER 5: RESULTS 63

Quasi-Carbon Supply *64*
Carbon Accounting Stance *65*
Regulatory Regime *67*
Carbon Stock Baselines *68*
5.1 MODEL SCENARIOS 69
Summary and Purpose of Model Experiments *71*
Scenario 1: BAU Baseline 71
Scenario 2: Initial Carbon Stock Baseline (Horizontal Baseline) 72
Baseline Summary 72
Scenarios 3 to 5: Restricted Regulatory Regime under 3 Carbon accounting stances 73
Scenarios 6 to 8: Relaxed Regulatory Regime under 3 Carbon accounting stances 73
5.2 RESULTS 74
5.2.1 Timber and Carbon NPV Results *74*
5.2.2 Net Present Value of Carbon *78*
5.2.3 Percentage of NPV Derived From Carbon *81*
5.3 CARBON SUPPLY, TIMBER SUPPLY AND REGENERATION RESULTS OF RESTRICTED MODEL CONFIGURATIONS (SCENARIOS 3 TO 5) 83
5.3.1 Carbon Supply for Scenario 4 ..... *85*
5.3.2 Comparison of Carbon Supply Under Different Carbon accounting stances (Scenarios 3, 4 and 5) *87*
5.4 EFFECTS OF REGULATORY REGIME ON CARBON SUPPLY 93
5.5 SUMMARY 99

CHAPTER 6: CONCLUSIONS AND AREAS OF FUTURE RESEARCH 102

6.1 POLICY IMPLICATIONS 104
6.2 LIMITATIONS 108
6.3 SUMMARY 109

LITERATURE CITED 110

List of Tables

Table 4-1	Transportation Costs Associated with Harvesting Specific Types of Logs From Supply Locations Given in $/ha	41
Table 4-2	Proportion of Inputs Transferred to Product and Bi-Products	42
Table 4-3.	Mill Price and Mill Capacity Parameter Assumptions	45
Table 4-4	Summary of Individual Yield Groups Obtained from Weldwood Inventory Data	46
Table 4-5	Aggregation of Yield Strata into Project Land Classes	47
Table 4-6	Aggregation of Natural Subregion Distinctions	48
Table 4-7	Summary of Final Yield Curve Development	50
Table 4-8	Site Index and Start Age of Fire Origin Yield Curves	51
Table 4-9	Site Index and Start Age of Basic Yield Curves	52
Table 4-10	Individual Yield Strata Transitions For Basic Management	53
Table 4-11	Individual Yield Strata Transitions From Basic to Intensive Management	54
Table 4-12	Carbon Class Ranges	60
Table 4-13	Long Run Fire Origin Carbon Class Starting Values	61
Table 5-1	Model Scenarios	70
Table 5-2	Combined Timber and Carbon NPV Results	75
Table 5-3	NPV of Carbon Results	80
Table 5-4	Percentage of NPV Derived From Carbon	82
Table A-1	Age Class Distribution: North	114
Table A-2	Age Class Distribution: South	114

List of Figures

Figure 2-1 Volume Accumulation of Aspen Other Hardwood Fire Origin Good Site 11

Figure 2-2 Carbon Pool Levels of Medium Class Pine Site of Basic Regeneration Origin with an Original Soil carbon Content of 125 Tonnes per ha. 12

Figure 2-3 Effects of Rotation Age on Fire Origin Aspen Stands of Site Class Good 15

Figure 2-4 Yield Curve of Pine Stand Regenerated by Basic and Intensive Management with an assumed 10% increase in yield for Intensive Management. 16

Figure 2-5 Carbon Development of Stands of Four Different Origins on Medium Productivity Pine Stand on a Medium Carbon Class Site with an Initial Carbon Stock of 200 tonnes per ha .. 18

Figure 2-6 Carbon Development of Stands of Four Different Origins on Medium Productivity Pine Stand on a High Carbon Class Site with an Initial Carbon Stock of 400 Tonnes per ha 18

Figure 3-1 Carbon Transfer After Harvest 36

Figure 5-1 Carbon Incentive accounts of BAU Baseline 66

Figure 5-2 Carbon Contained Carbon Incentive Account Baselines 73

Figure 5-3 'Quasi' Carbon Supply Curves for the First Two Periods With Incentives on Forest Carbon 85

Figure 5-4 Timber Supply Under Restricted Forest Carbon Account 86

Figure 5-5 Area Harvested and Regenerated under Restricted Forest Carbon Account 87

Figure 5-6 Total Carbon Stocks of Restricted Scenarios at Carbon Prices of $2/t and $10/t 89

Figure 5-7 Carbon Credits Supplied By Forest Carbon From a BAU Baseline Under Scenario 3 Through 5 in Periods 1 and 2 at Carbon Prices of 1$/t and 2$/t 90

Figure 5-8 Total Carbon Supplied Under Scenario 3 Through 5 in Periods 1 and 2 92

Figure 5-9 Total Carbon Stocks of Unrestricted Scenarios Under 3 Carbon accounting stances 94

Figure 5-10 Total Carbon Stocks in Restricted and Unrestricted Forest Carbon accounting stances 95

Figure 5-11 Carbon Supplied Under Restricted and Unrestricted Forest Carbon Accounts in Periods 1 and 2 96

Figure 5-12 Timber Supply Under Restricted and Unrestricted Forest Carbon Account 97

Figure 5-13 Total Area Harvested and Regenerated by Restricted and Unrestricted Forest Carbon accounting stances 98

Figure 5-14 Carbon Supplied Under Scenario 3 and 6 in Periods 1 and 2 99

Figure 5-15 Carbon Supplied Under Scenario 5 and 8 in Periods 1 and 2 99

Chapter 1: Introduction

Given that forests and the products that emanate from them literally embody carbon, few segments of Canadian society are more intricately linked to the climate change issue and the implementation of the Kyoto Protocol than the forest sector.

Taken from "Forest Sector Table Options Report" by NRC, 1999

1.1 Introduction

Addressing climate change has been an international issue since 1979 when the first World Climate Conference was held in Geneva. Since this time there have been numerous international attempts to address the issue including the formation of the International Panel on Climate Change (IPCC) and numerous Conference of the Parties (COP) meetings. It was at COP3 in Kyoto, Japan that Canada and numerous countries worldwide signed the Kyoto Protocol thereby agreeing to reduce their emissions of CO_2.[1]

As trees grow, the process of photosynthesis converts CO_2 into sugars and ultimately fibres. It is these fibres that enable trees, and other plants to store carbon for extended periods of time thus creating a sink. Storing carbon in a sink, such as in forests, can be thought of as equivalent to emission reductions as the result is a net reduction in atmospheric carbon. Offsetting, or storing, carbon may be more economical than direct emission reductions and therefore is an option that should be examined. One potential area that is drawing increased interest and research is the potential of forest ecosystems to store, or sequester, carbon.

The Kyoto Protocol was designed to allow countries flexibility in meeting commitments and provides the option of including land use practices in areas such as forestry in Articles 3.3 and 3.4, which address "afforestation, reforestation and deforestation" and "Human induced activities related to...land use change and forestry", respectively. Articles 3.3 and 3.4 of the Kyoto Protocol recognize that measures to deal with climate change should cover all relevant sources, sinks and reservoirs of greenhouse gases (GHG's) including forestry.

Canada, and in particular, Alberta have heavily resource dependent economies. This implies that in the face of a carbon constrained economy they could be impacted heavily. Implementing climate change policies should allow regions to be able to take full advantage of its resources to mitigate the effects of climate change and climate change policy (National Climate Change Process, 2000). One such resource that has a large potential to aid Canada in meeting its Kyoto commitments is its' forests. Forests may provide an opportunity for Canada to take advantage of the large quantity of carbon stored in these ecosystems.

The Canadian government fought hard to have carbon sinks (both agricultural and forestry) included as a means of meeting targeted reductions and it appears that Canada may have secured itself an advantage relative to other signatory countries given the potential for Canada's forests to store vast amounts of carbon (Natural Resources Canada, 1999). As a result of negotiations forest carbon sinks can be counted towards up

[1] Upon signing the Kyoto Protocol in 1997, Canada agreed to reduce their GHG emissions by 6% from 1990 levels. Current estimates state that this is equivalent to a 30% reduction form what emissions are

to 77 mega tonnes (Mt) of Canada's emission targets during the first commitment period (2008-2012).[2] Canada must now decide whether or not it should make use of these articles as a way of achieving its targeted reductions.

1.2 General Problem and Previous Research

As a result of Canada's ratification of the Kyoto agreement in December of 2002, Canada has committed to reduce carbon emissions and must report on and account for carbon stock changes from 1990 to the first commitment period in 2008-2012 that result from afforestation, reforestation, and deforestation (ARD). Changes in carbon stocks related to afforestation and reforestation activities represent a credit towards Canada's emissions cap, while changes in carbon stocks related to deforestation activities represent a debit. Parties of the Kyoto Protocol have recently agreed on many of the rules for implementation of the protocol, including the rules for the inclusion of forestry carbon sinks in the Kyoto Protocol (Climate Change Central, 2002).

The decision to ratify the accord has made it necessary to make another important decision regarding carbon sinks. According to Article 3.4 of the Kyoto Protocol, countries are allowed to claim a credit for forest management activities that alter the sequestration potential of the forest. Canada must make a decision regarding the use of Article 3.4 by 2006, and must decide whether the use of forest sinks is a wise choice.

---

expected to be in 2008 under a business as usual scenario (NCCP, 2000).
[2] A mega tonne is one million tonnes.

The purpose of this research is to develop an economic model, which can be used to identify potential issues associated with Canada invoking Article 3.4 of the Kyoto Protocol. In assessing if Canada should invoke Article 3.4, it is necessary to estimate the benefits, costs and risks associated with including forest sinks as a means of generating carbon credits. Given the tradeoffs in using forests as a carbon sinks (i.e. increases in carbon stocks are often the result of decreases in harvest levels), the provision of fibre for production of timber products and the importance of the forest products industry in Canada, this is an important current policy issue.

Current discussions on climate change issues suggest that some form of carbon emission constraints will exist in the future. A variety of policy options for reducing carbon emissions have been considered for use by Canada, including direct emission reductions, and carbon sequestration and storage in both geologic and biologic systems.[3] While there appear to be a variety of options available, they vary in terms of the costs and benefits they generate. Canada may wish to the examine both the role that forests and forest carbon play in mitigating atmospheric CO_2 levels in addition to direct emission reductions (Van Kooten *et al.* 1999).[4] The lack of inexpensive options led Canada to push for the inclusion of forest and agricultural sinks in international negotiations as a means of buying the time to develop better and cheaper technologies needed to reduce

[3] The National Climate Change Process (NCCP) outlines various industry specific options. These can be found at the following website: http://www.nccp.ca/NCCP/national_process/issues/index_e.html

[4] Mitigation and abatement measures are the two most common approaches to respond to and moderate the impact of climate changes. Mitigation measures limit the net amount of green house gases (GHG's) that accumulate in the atmosphere and include emission reduction and sink enhancement, which includes options that remove carbon after it has been dispersed into the atmosphere (Bruce *et al.* 1996). Adaptation is a means of addressing climate change through activities that are undertaken in response to climate change or in response to mitigation strategies to limit the effects of climate change (Hauer *et al.* 2001).

emissions to targeted levels without significant reductions in economic activity. Canada has secured what some see as a significant advantage among Parties to the Kyoto Protocol by negotiating for a broad range of forest carbon management (FCM) activities (Pollution Probe, 2002). These methods vary in their cost effectiveness, equity and their reduction potential, and as a result Canada has numerous difficult decisions to make.

The storage of carbon in various components of the forest ecosystem has led to difficulties in the determination of appropriate carbon accounting stance. For the purpose of this study, a carbon accounting stance is the collection of carbon pools, which have positive carbon values placed on them. Currently, it is uncertain if only the carbon contained in the merchantable component of the tree should be counted towards the generation of carbon credits. This is further complicated by the vast amount of carbon contained in other carbon pools of the forest such as the carbon contained in forest soils or roots. An extension of the carbon accounting framework problem involves the discussion of whether carbon stored in forest products should be counted. It is this confusion surrounding which carbon pools provide the appropriate carbon accounting framework that forms the basis for this study.

The purpose of this study is to examine the effects of carbon incentives on forest management by developing a linear programming model. Using this model, various carbon incentive stances are proposed, examined and the resulting forest management decisions are discussed.

1.3 Research Objectives

This study aims to advance existing literature related to carbon reduction and incentive mechanisms for carbon sequestration on forestlands and to provide valuable information to forest managers regarding the effects of incentive mechanisms on forest management. The objectives of this study are fivefold.

1. Develop a linear programming model of forest management that incorporates forest harvesting and regeneration activities while accounting for timber stocks, living biomass carbon stocks, soil carbon stocks, age class dynamics and harvest dynamics. This model provides a framework that is used to address remaining research objectives.
2. The second objective of the study is to estimate carbon credit supply curves for a forestry firm under alternative carbon incentive packages defined mainly by the carbon accounting system.
3. The third objective is to examine how a carbon accounting stance affects the optimal forest management plan. In particular, how do incentives affect timber supply and harvest/regeneration prescriptions of the forest? This study also examines how the provision of carbon incentives under various accounting systems affects the supply of forest products.
4. The fourth objective of the study is to examine the effects of baselines, discussed in detail in chapter 5, in the supply of carbon and generation of carbon credits via forests.
5. The fifth objective of this study is to examine how forest regulations, such as regeneration regulations and even-flow constraints, affect carbon supply.

1.4 Thesis Structure

This study continues with a discussion of the literature and past research related to the subject of forest carbon sequestration in chapter 2. Chapter 3 provides the formulation of the model used in this study. Chapter 4 describes the forest inventory data used and includes a discussion of calibration of the model and carbon budget simulations. Chapter 5 provides a description of baseline scenarios and a detailed description and analysis the various model scenarios designed to explore the effects of different carbon accounting stances on forest management. Also included in Chapter 5 is an examination of the likelihood of a forest products firm entering into a carbon credit trade with a firm seeking offsets. Chapter 6 provides some concluding comments in addition to providing policy implications and recommendations for future research.

Chapter 2: Background

Carbon sequestration may provide an opportunity to reduce the effects of global warming by taking advantage of the natural ability of forests to store carbon. However, there is still a large amount of uncertainty surrounding the use of forest carbon sequestration in global warming mitigation. The purpose of this chapter is to provide some background knowledge necessary to understand forest carbon sequestration issues and uncertainties, including background knowledge on carbon dynamics and supply. The first section of this chapter provides a summary of the biology of carbon sequestration in forests. The chapter continues by providing a summary of how forests can be manipulated to enhance carbon stocks as a means of changing the carbon levels present in the forest. This section is followed by a summary of the economics of carbon sequestration. The fourth section of this chapter provides a discussion of the policy issues of forest carbon sequestration. The final section provides some concluding remarks.

2.1 Sequestering Carbon with Forests: Biological and Physical Aspects

In order to address carbon sequestration in forestry it is first necessary to define a few terms. Carbon cycling is a term used to describe the movement of carbon through the biotic and abiotic components of the Earth and our atmosphere. In the forest carbon cycle, described below, carbon cycling is used to refer to the movement of carbon through the various components of the tree, soils and dead organic matter pools. Sequestration is a term used to refer to the net additions to a stock, or pool, of carbon in a given period. Sequestered carbon may include carbon in forests and as well as carbon stored in forest products both in use and not in use (Kurz *et al.* 1998). Sequestration in

trees is a natural process that can be altered by human intervention and therefore is of interest to policy designers. Objects that absorb and store carbon, such as the oceans and trees, are carbon sinks or sequesters. It is the ability of forests to act as a sink that has identified them as a potential tool to address climate change. However before forest carbon sequestration can be used as a tool, it is necessary to understand the carbon cycle of the forest.

The Forest Carbon Cycle

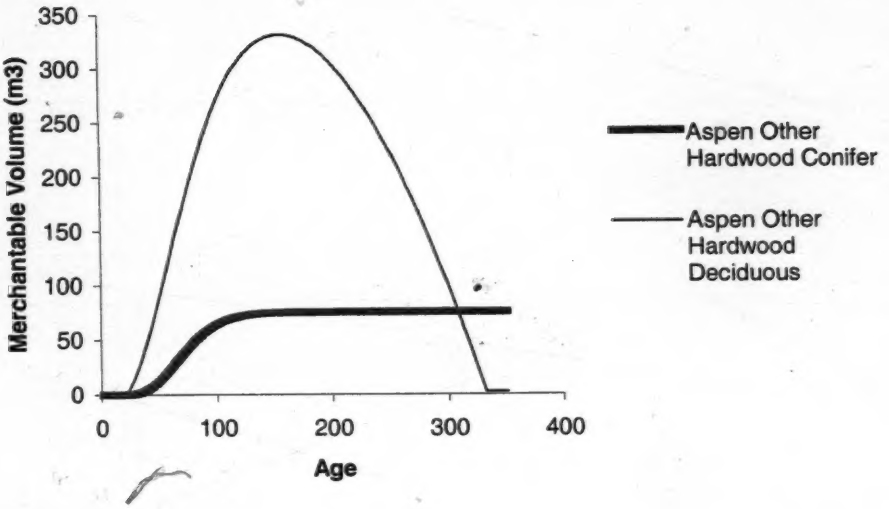
Forests have an important role in mitigating climate change in the short run through the carbon cycle (van Kooten *et al.* 1995). The process of photosynthesis removes carbon dioxide (CO_2) from the atmosphere, and stores it in biomass in the form of carbohydrates until it's release by combustion, decay or processing (Kurz *et al.* 1992). Since trees are long lived and the products derived from them, such as lumber, are long lived, carbon can be stored in both forests and forest products for extended periods. This ability to store carbon for extended periods makes both the use of forest ecosystems and their products potentially attractive alternatives to traditional greenhouse gases (GHG) policies such as point source reductions.

Carbon is stored in a wide range of carbon pools in the forest. These include soil carbon in forest stands, the living tree, shrub and herbaceous vegetation biomass, peatlands and lakes. It is important to consider the various pools in which carbon is stored as policies may be designed around a narrow definition of forest carbon, such as one that strictly looks at the carbon in the merchantable component of the tree, or a broad

definition of forest carbon, such as one which would include carbon in peatlands as well as carbon contained in the tree and other pools. Here we define forest carbon as the carbon included in the merchantable component of the stand as well as the carbon contained in the un-merchantable components of the stand such as branches, leaves and roots, and carbon contained in other living components of the forest such as shrubs and herbs and carbon contained in the soil. To effectively address forest carbon sequestration as a climate mitigation tool it is necessary to have an understanding of stand level carbon dynamics.

Stand Level Carbon Dynamics

An understanding of stand level carbon dynamics is essential to addressing forest carbon sequestration because many management actions that can influence aggregate carbon stocks at the forest level are carried out at the stand level. Such actions include harvest rotation selection and silvicultural operations that enhance stand growth. In a natural forest stand, biomass stocks increase in a sigmoidal or S shape. In some stands biomass may decrease at older ages. An example of deciduous and coniferous growth curves obtained from the Weldwood FMP for an Aspen-Hardwood Good site of fire origin is included in Figure 2-1. This figures illustrates the rapid initial growth of hardwood stands followed by a decline in volume as the tree rots. The coniferous component of the stand exhibits a slower rate of growth that reaches a sustained carbon stock level that is lower than the deciduous component.



Source: Weldwood 1999 FMP

Figure 2-1 Volume Accumulation of Aspen Other Hardwood Fire Origin Good Site

As trees grow, they sequester or store carbon in all living biomass. This includes not only the merchantable bole of the tree but also the tops, foliage collectively referred to as above ground biomass. Root biomass (both fine and coarse roots) can represent a significant proportion of total ecosystem biomass since a large proportion of annual photosynthetic production is allocated to below ground biomass components (Kurz *et al.* 1996)[5]. The magnitude of biomass stored in the various components of the stand, called 'pools', originating from a natural disturbance is illustrated in figure 2-2. Figure 2-2, obtained through simulations, illustrates the carbon stock levels of a pine stand of basic regeneration origin on a medium site where basic regeneration origin is representative of current regeneration practices. This figure illustrates that a large amount of carbon in boreal and northern forests is stored in the soil and significant amounts of carbon in the

[5] Below ground biomass consists of below ground living biomass including fine and coarse roots.

merchantable components of the stand. Substantially less carbon is stored in the above and below ground carbon pools.

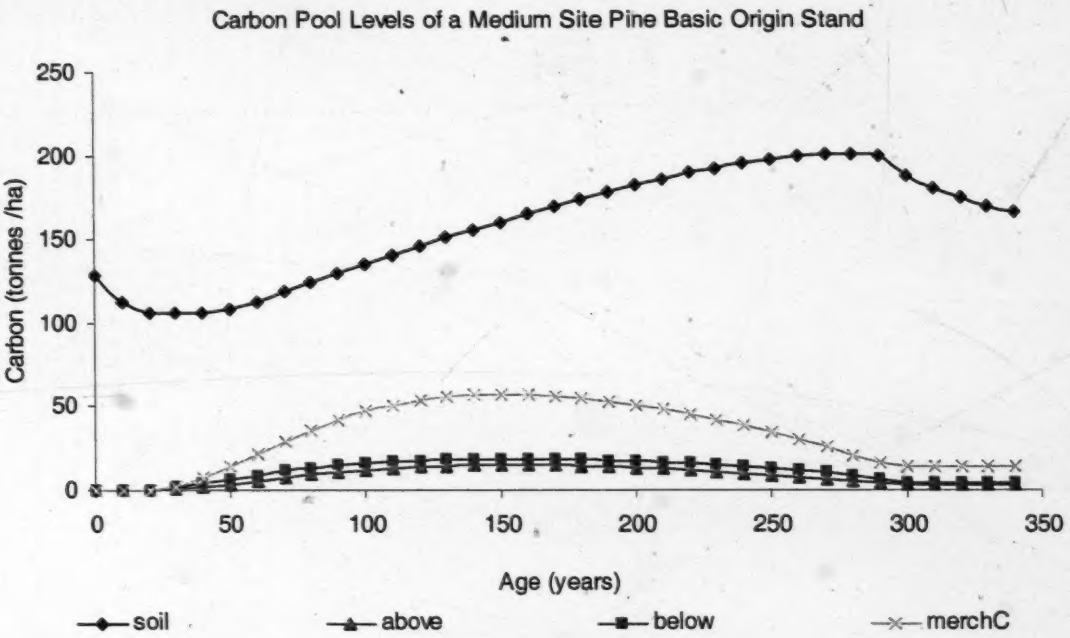


Figure 2-2 Carbon Pool Levels of Medium Class Pine Site of Basic Regeneration Origin with an Original Soil carbon Content of 125 Tonnes per ha.

As trees continue to grow, natural processes such as dieback and annual leaf litter, cycle carbon throughout the forest ecosystem. Overtime carbon from dead organic matter (DOM) that falls from the trees (i.e. dead branches, foliage, and roots) becomes incorporated in the soil. This material is subjected to a decay process that releases carbon back into the atmosphere. The relative importance of the various carbon pools in the sequestration of carbon varies with stand age, region, forest type, site productivity and management intensity (Adams *et al.* 1999).

Over extended periods of time, carbon may build up in the soil due to the addition of more carbon than is being released. Therefore, it is possible to have large amounts of carbon in the soil at the beginning of a stands life (see Figure 2-2). In addition, carbon may be added to the soil when dead organic matter is left on the site after disturbances such as fire or harvesting. These types of materials tend to decay at a faster rate than the new carbon added during the initial growth of a new stand. Faster decay rates, at early stages of stand development, are due to both the initial slow growth of new stands and increases in forest floor temperature due to open forest canopies early in forest stand development, which increases decay processes (Kurz *et al.* 1992). This initial decline after disturbance is not permanent, and over time carbon stocks in the forest soils will begin to increase again as new dead organic matter from leaf drop, dead branches and natural tree mortality is added to the soil. The initial decline and subsequent rise in dead organic matter of a stand can be seen in figure 2-2. The development of carbon pools in a stand over time determines the development of forest carbon over time. Human intervention has the potential to change the shape of these stand level curves and therefore alter the development of forest carbon over time.

2.2 Manipulation of Carbon Stocks

Although carbon is present in the forest naturally, there exists potential to manipulate the levels of forest carbon pools and fluxes, and therefore atmospheric concentrations, through human activities (Apps and Price, 1996). Activities, which affect the biomass levels of a stand, can be used to manipulate the carbon present in the forest. Activities which can be used to manipulate carbon levels include pre-commercial thinnings, commercial thinnings, manipulation of rotation ages, pruning, and alteration of

the amount of slash used as bio-fuel (Woodrising Consulting Inc, 1999). The rates at which forests sequester carbon in the future depend on how the forest is managed today. As a result management decisions should take into account how they affect the forest's ability to absorb carbon (Plantinga and Birdsey, 1994).

In order to illustrate the potential impacts of management on forest development, the carbon budget model of Kurz *et al.* (1992) was used to simulate the impacts of various management regimes on carbon stocks at the stand level. The management regimes examined include one to examine the effects of current management practices (basic), one to examine the effects of intensive forest management (intensive) and one to examine the effects of no management (extensive). Further detail on the carbon budget model, including a full model description and description of parameters used in the model are described in Kurz *et al.* (1992), Apps *et al.* (1999) and Kurz and Apps (1999).

Two possible methods of manipulating carbon content of forest stands are manipulation of harvest age and of the growth trajectory of the forest. Manipulating harvest ages can increase the carbon present in the forest if harvest ages are increased (delayed harvest) which allows carbon to remain and accumulate in the stand for longer periods. Figure 2-3, obtained from carbon budget model simulations, illustrates the effects of delaying harvest on the carbon present in a fire origin aspen stand on a good site with an initial carbon stock of 200 tonnes per ha. The figure shows that a delay in harvest by one period (10 years) increases both the maximum and the average carbon

present in the stand originating in period T0. The increase in carbon levels can be attributed to the additional growth that occurs in the additional period prior to harvest.

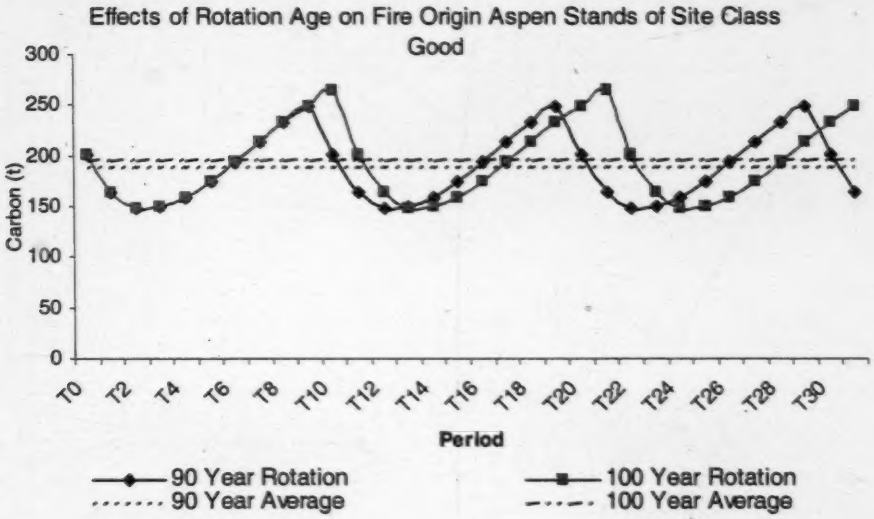


Figure 2-3 Effects of Rotation Age on Fire Origin Aspen Stands of Site Class Good

Manipulation of carbon sequestration rates can also be achieved by increasing the growth rates of trees, such as by fertilization, thereby encouraging faster carbon sequestration. Another means of manipulating the growth trajectory of a forest involves species manipulation. A stand of slow growing species can be replaced with faster growing species, which sequester carbon at faster rates although it may have a negative impact on biodiversity. Figure 2-4 illustrates how the volume of a stand can be manipulated due to increases in management intensity by comparing carbon stocks for hardwood and softwood living carbon pools under two different management regimes. The basic management regime represents current practices while the intensive method represents investments in silviculture to increase volume. Here it is assumed that intensive management involves species manipulation to increase the pine component of

the stand by 10%. The figure shows both the hardwood and softwood yield curves of a pine stand growing on a good site, for two types of regeneration after disturbance.

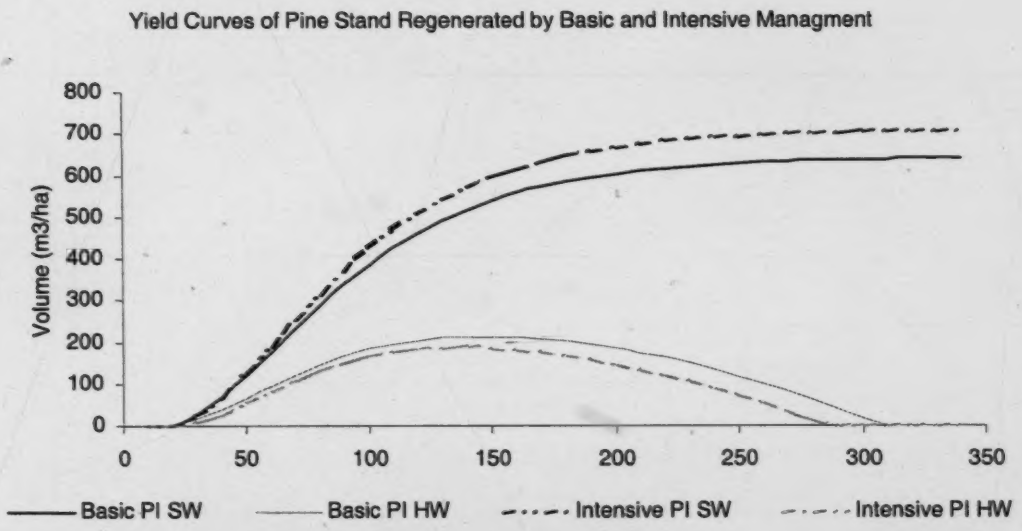


Figure 2-4 Yield Curve of Pine Stand Regenerated by Basic and Intensive Management with an assumed 10% increase in yield for Intensive Management.

Forest Level Carbon Dynamics

Forest level carbon is simply the summation of stand level carbon, and forest carbon dynamics explains how forest carbon levels change over time. Hence by manipulating either the harvest age or the yield trajectory it is possible to change the path of carbon over time at the stand level and by extension over a whole forest.

Canada's forests are dynamic in nature and are subject to frequent disturbances including fires and insect outbreaks. Fire is a natural and necessary force, shaping Canada's landscape and ensuring healthy growth of new forests. National estimated losses range between 0.1 – 2% of forested area due to forest fires and 1-10% due to insect

and diseases (CCCFM, 2002 and SBSTA, 2000). Fires release carbon into the atmosphere through combustion and insect and disease outbreaks release carbon into the atmosphere as a result of decomposition. Both fires and insect and disease outbreaks have the potential to have significant effects on carbon stocks by reducing the biomass present in the forest. The effects of fires on forest carbon stocks can be substantial as have been estimated by Kurz *et al.* (1992) and Canada's Greenhouse Gas Inventory (1990-1999). A recent paper by Amiro *et al.* (2002) demonstrated the magnitude of forest fire emissions in Canada and suggested that in years of large events, CO_2 emissions from forest fires rival those of the transportation sector.

Figures 2-5 and 2-6 illustrate the path of carbon over time that is generated by both natural forces and human management when the stand is disturbed in year zero. The figures show simulated carbon stocks from the carbon budget model of Kurz *et al.* (1992) for 3 human management regimes and one forest fire regime, collectively referred to as disturbance regimes, at the stand level for a medium pine site with two initial levels of carbon stock. Figure 2-5 illustrates the effects of the 4 disturbance regimes on the carbon levels of a pine stand of a medium site class of medium initial carbon class described in detail in chapter 3. Figure 2-6 illustrates the effects of the 4 disturbance regimes on the carbon levels of a pine stand of a medium site class of high initial carbon class. These figures illustrate the potential effects of management and fire on the carbon development of a stand. Management levels represent the decision that forest managers make and modeling these decisions is one of the objectives of this study. A forest manager may decide to invest in various practices that alter the development of a stand

over time. In order for a forest manager to determine if they should invest in intensive forest management, it is necessary examine the economics of carbon sequestration, which is the subject of the next section.

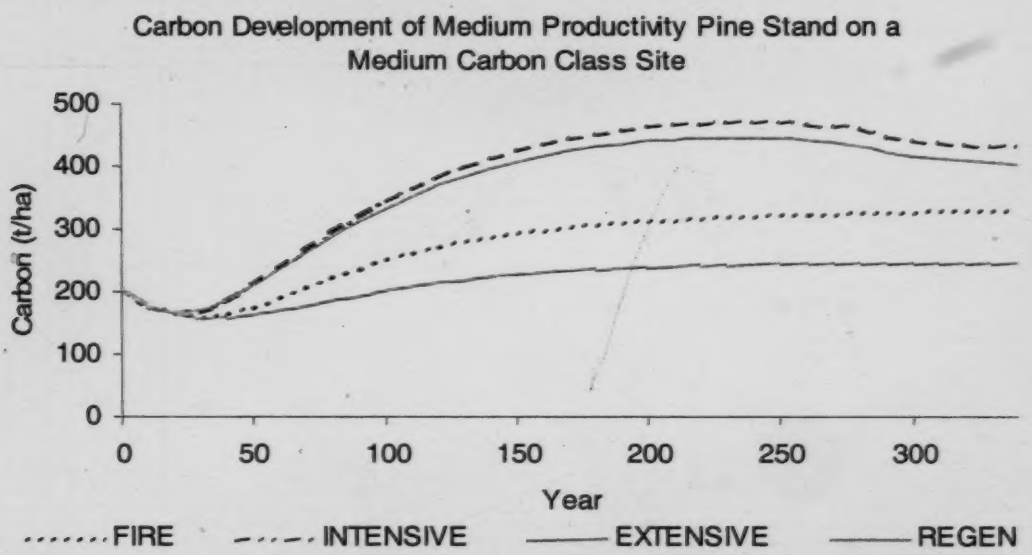


Figure 2-5 Carbon Development of Stands of Four Different Origins on Medium Productivity Pine Stand on a Medium Carbon Class Site with an Initial Carbon Stock of 200 tonnes per ha

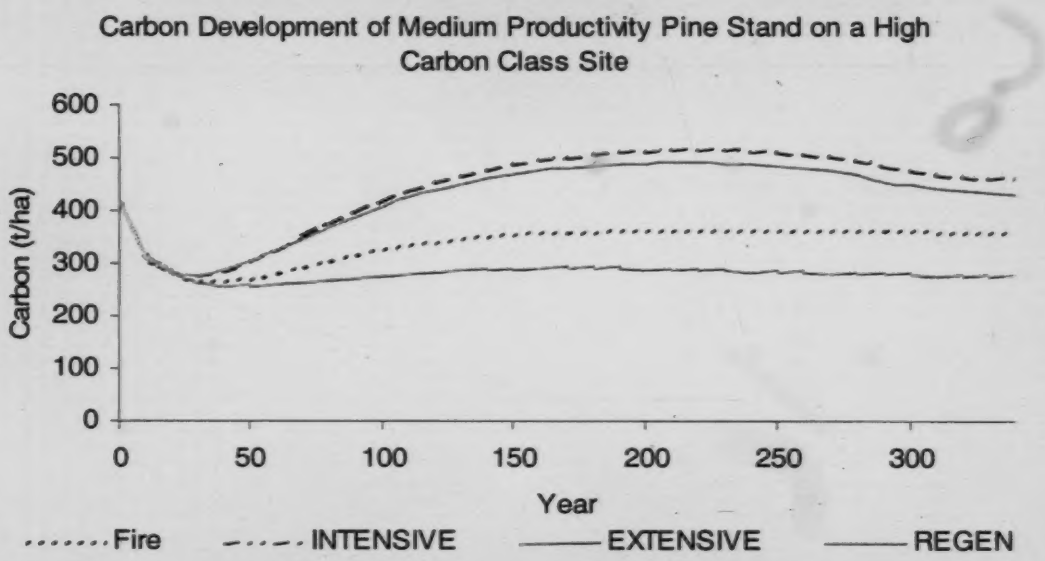


Figure 2-6 Carbon Development of Stands of Four Different Origins on Medium Productivity Pine Stand on a High Carbon Class Site with an Initial Carbon Stock of 400 Tonnes per ha

2.3 *Economics of Carbon Sequestration*

Various studies have examined the economics of forest carbon sequestration. These studies can be divided into 2 streams: the first consists of single rotation models which examine the effects of carbon values on rotation ages; the second consists of whole forest models which examine the effects of carbon values on an aggregation of many stands, subject to an age class distribution and various global constraints such as demand constraints and carbon stock constraints. This section begins with a review of the single rotation literature and is followed by a review of the literature on whole forest models.

Single rotation models examine the effects of carbon prices on the optimal management regime of a forest stand, including rotation or cutting cycle, regeneration prescription and thinning regimes. Many of these studies examine the effects of carbon values on rotation ages. Sedjo (1999), Englin and Callaway, (1993) and (1995), Plantinga and Birdsey (1994) showed, using single stand rotation models, that a positive price on carbon results in an extension of the optimal rotation age or delayed harvest, and that under sufficiently high carbon prices, it is optimal to delay harvest indefinitely. Studies by van Kooten *et al.* (1995) and (1997), and Hoen and Solberg (1994) examined the effects of taxes and subsidies of carbon on the forest using single rotation models and concluded that carbon taxes and subsidies delay harvest.

Recent studies including van Kooten *et al.* (1999) have focused on the use of plantations and other studies by Adams *et al.* (1993) *and* (1999), and Alig *et al.* (1999) focus on land use change and afforestation van Kooten *et al.* (1999) suggest that Canada will rely to some extent on afforestation of marginal agricultural lands to reduce GHG

emissions. The study identifies 7 million ha of marginal agricultural lands in Alberta and BC as potential afforestation areas and examines the cost effectiveness of afforesting these areas. The authors conclude that the final use of wood has a large effect on the area that can reasonably be forested concluding that a minimal area can reasonably be afforested if wood is used for fuel substitution, but nearly one third of the land could be afforested to trees when the carbon is stored in wood products.

Whole forest models, which examine the effects of carbon values on an aggregation of many stands, subject to an initial age class distribution and global constraints, comprise a second type of model that attempts to examine the effects of carbon on forest management. Whole forest models have been used to examine the effects of fire frequency reductions, land use changes and carbon prices through the use of carbon supply curves where supply is the quantity of carbon supplied at different carbon prices.

Sohngen and Hayes (1997) use a whole forest model to assess the effects of fire frequency on the carbon balance of forestlands. The study examines the effects of fire frequency reductions on carbon pools and also examines the economic effects of such a reduction at a regional level. They conclude that a reduction in fire frequency from its current level (1984-1990) might result in an increase in carbon storage in unreserved U.S. timberlands from a period of 1990-2040.

A study by Alig *et al.* (1997) use a whole forest model and product and land markets in the U.S. forest and agricultural sectors to examine the implications of private forest management, land use and carbon sequestration policies. The authors drew four conclusions from this study: (i) policy induced land use change may generate compensating land use changes through markets, (ii) policy induced land use change do not have to be permanent, (iii) the implementation of land use and management changes of a regular fashion may not be optimal, and (iv) primary forms of adjustment to meet carbon policy targets involve shifting of land from agriculture to forest and more intensive forest management in combinations varying with the policy target.

Sohngen, Mendelsohn and Sedjo (2001) use a dynamic timber supply model that provides time profiles for a number of important variables including forest biomass, timber harvests, and associated forest carbon to estimate carbon supply curves for global forests and other land uses. The authors estimated "long-term, cumulative, carbon quasi-supply curves" under different price scenarios and different time periods.[6] They demonstrate that cumulative carbon quasi-supply curves could be generated through forestry although it significantly depended on initial carbon prices and expectations regarding the time profile of future carbon prices. They also concluded that long-run quasi supply curves generated from a constant price have different characteristics than quasi supply curves generated from expectations about rising carbon prices through time.

[6] The authors use the term 'quasi supply curve' because the curves described are not steady-state curves however they do represent the relationship between the amount of carbon cumulatively sequestered between the base year and the selected year.

2.4 Policy Issues

There are 4 major policy issues involved in using forests as a carbon sink. These include; determining the appropriate type (e.g. tax or carbon trading contracts) and duration of incentives; establishing a credible baseline; regulatory regime including even-flow regulations; and determining the scope of carbon incentives in terms of what carbon pools should be included (living biomass, soil biomass, forest products).[7]

If carbon sequestration in forests is to be a viable option for carbon management it is first necessary to determine what mechanisms can be used to encourage forest carbon sequestration. One option is to tax the harvest of timber, thus delaying the harvest age. Another option is to subsidize timber owners for increasing their carbon stock, relative to a baseline, thereby increasing the amount of biomass present in the forest.[8] The program most often discussed is a combination of the two, which subsidizes forest growth and taxes carbon losses. One final method of achieving carbon sequestration, and the focus of this thesis, is the development of a trading arrangement where by contracts for sequestered carbon are bought and sold in a market. Within a contract system there is an opportunity for producers in the forest sector to remove and reduce GHG emissions and generate credits (or offsets) that can be sold to sectors that face higher GHG control costs.

Buying and selling carbon credits, also called carbon credit trading, is attractive for two reasons. The first is because although taxes could be effective too, to date, there

[7] A baseline serves as a reference point to monitor changes in carbon levels as a result of changes in management.
[8] The issues surrounding baselines are discussed in section 5.1.

has been little mention of carbon taxes and their use has been excluded from domestic policy options for implementing the Kyoto Protocol. The second reason is due to the jurisdictional issues surrounding the management of Canada's forests. The use of a carbon credit trading system will eliminate some potential conflicts between provincial and federal governments. Imposition of carbon taxes on timber harvest for example would probably be perceived as a Federal entry into an area of provincial jurisdiction. Carbon credit trading would side step this problem by avoiding taxation of provincially owned resources.

Once the appropriate type of incentive is selected, it is necessary to determine the appropriate duration of that incentive. Currently it is uncertain whether incentive packages should end at the end of the first Kyoto period (2012) of if they should be extended beyond the first commitment period. The targeted reductions set to occur in the commitment period of 2008-2012, lead to problems regarding what happens when the Kyoto commitment period is over. This uncertainty makes it difficult for forest managers to consider changes in management practices that would have impacts beyond 2012 and may result in incentives to reduce carbon stocks immediately after the first commitment period if appropriate incentive mechanisms are not in place for maintaining the sequestered carbon.

Regardless of the mechanisms and duration chosen, it is necessary to determine an appropriate baseline for forest carbon stocks, as carbon credits in forest sinks are generated by comparing actual carbon growth (or decay) in a forest to carbon growth (or decay) along a predetermined baseline. Presently it is unclear what the baseline is for

forest management under Kyoto article 3.4. For afforestation and deforestation under article 3.3 the relevant change is the net change in forest carbon stocks on areas classified as afforested and deforested during the commitment period from 2008 to 2012. If forests other than afforested and deforested lands are to be used as offsets for emissions reductions, rules for determining credit are not determined, although it seems to be the case that changes in carbon stocks in the period from 2008 to 2012 are what is relevant. In an existing managed forest there exists a carbon stock with a pre-existing trajectory of carbon stocks over time that could be used to determine a baseline.

As discussed above, a suitable baseline over a wide forest area is necessary to determine carbon credits. One possibility is to use the projected 2008 stock level as the baseline. However, there is the potential that Canada's forests, which are mature, may be declining during the 2008 to 2012 period. Therefore a declining baseline may be more appropriate. It is not clear, however, that this would be acceptable. In addition, if the 2008 stock level is to be used as a basis for comparison in generating carbon credits there will be an incentive to opt out of using forestry sinks to generate credits if carbon stocks are expected to decline during the commitment period.

Determining a baseline is not a simple task as there are many issues associated with its establishment. It may be determined that a business as usual (BAU) baseline is the most appropriate. In this situation a baseline would be determined by simulating the carbon stocks that would result from a combination of existing management processes such as harvesting, replanting and silvicultural intensity and natural forest growth and

existing levels of disturbance processes such as fires, insects and disease. The combination of these processes will determine the baseline.

However, natural disturbance processes are inherently uncertain or stochastic in nature. For example, fire activity has been negligible in the Foothills model forest over the past 50 years yet prior to 1950 fires were relatively common. It is uncertain if the change is a result of management, or simply part of the natural disturbance cycle, or is the change a combination of both. Establishing a credible baseline based on a BAU scenario that includes potential natural disturbances is therefore difficult. Given the many uncertainties surrounding the establishment of baselines, two baselines are included in this study and are discussed in detail in 5.1.

It should be noted that the ability of forest managers to freely make decisions regarding delayed harvest and enhanced forest management in Canada is severely limited by current forest policy. In Canada, most forestland is publicly owned and as a result, timber supply and prices are determined administratively by a combination of policy considerations, social values and biophysical characteristics (Williams, 1994). As a result it may be difficult to forecast or model the impacts of climate change on Canadian timber supply and timber markets (Hauer *et al.* 2001).[9] Given this regulatory environment, it is also important to note that ownership of credits is not certain. Given that tenures are on Crown lands, provincial governments may argue that they own the

[9] It should also be noted that van Kooten and Arthur, (1989) suggest that any changes in Canadian and global forest endowments will likely have implications on international trade and prices of forest products. Thompson *et al.* (1997) extend this to suggest that these changes in prices and timber supply will affect government resource revenues and costs of management and resource development.

credits generated on those lands. Since ownership is necessary to carry out a trade with a carbon credit buyer, it may not be possible for forest managers operating on Crown land with use rights or leasing arrangements to obtain the rewards for investments made to generate credits.

The scope of carbon incentives may have an effect on forest carbon levels. To effectively encourage forest carbon sequestration practices, it may be necessary to include all carbon pools (above ground biomass, below ground biomass, soils and forest products) in the incentive structure. It is likely possible to determine the amount of carbon stored in the living biomass component of the forest given the amount of information available on aboveground biomass and its dynamics using standard inventory techniques. The amount of information available with respect to above ground biomass is many times greater than that for root biomass (Kurz *et al.* 1996). Hence it will be much more difficult to obtain good estimates of below ground biomass and perhaps even more difficult to measure is soil carbon, especially over large forest areas (Kurz *et al.* 1996). This makes it plausible that soil carbon and/or below ground biomass might not be included in a carbon incentive stance. This makes it necessary to simulate carbon incentive policies that both include and exclude soils in order to determine the potential worth and impact of including these components in incentive stances. It is also important to examine the relative effects of forest product credits to wood industries. The breadth of carbon incentives examined in this study is discussed further in section 5.1.

2.5 Summary

In this chapter the background information necessary for the discussion of forest carbon management was presented including a discussion of the biological and physical aspects of forest carbon. A discussion of how to manipulate carbon stocks is also included at both the stand and forest levels. The two methods most often discussed as a means of manipulating carbon stocks are (i) manipulation of rotation ages; and (ii) manipulation of the growth trajectory of a stand. A summary of the literature on the economics of carbon sequestration concludes that (i) rotation lengths of existing forests should be increased; (ii) that carbon sequestration in forests may be a relatively cheap option although it may have a limited impact at the national level; and (iii) that reducing rates of fire frequency may be a viable option to address forest carbon management. The section on policy identifies potential policy formats and identifies policy barriers that need to be addressed such as baseline formation and details of carbon incentives.

To conclude, there are many complexities and uncertainties, both on the science and policy front, associated with forest carbon sequestration that will inhibit firms from acting to sequester carbon in forests. In order for forest carbons sequestration to be widely adopted, it is first necessary to clarify the uncertainties on the policy side. Once clarified, it may be possible to design incentive mechanisms to enable and encourage forest carbon sequestration. The following chapter provides a discussion of the model used to examine the effects of various incentives given the obstacles identified in this chapter.

Chapter 3: A Forest Management Scheduling Model with an Integrated Carbon Budget Model

One of the major objectives of this study is to examine the effects of various carbon incentive stances on forest management in a manner that would allow for the tracking of carbon pools, harvest and regeneration packages, species composition and management practices. Scenarios are designed to estimate carbon supply under different constraints where carbon supply is the quantity of carbon sequestered relative to a baseline. The model described in this chapter is also used to develop 'quasi' carbon supply curves. The supply curves are 'quasi' supply curves because the developed curves are based on carbon prices held constant through out the planning horizon. To accomplish this objective, a mathematical programming approach is used. In this chapter the mathematical formulation is specified. The data used to calibrate the model are described in chapter 4.

3.1 Model Formulation

In order to examine carbon supply under various policy scenarios, it is necessary to design a model that allows policy related assumptions to easily be changed, including carbon price, the regulatory environment and the scope of carbon accounting stance. The problem being addressed in this study can be described using optimization techniques that are used to determine harvest rates and species regeneration when various carbon incentive accounts are offered. The model is a forest management scheduling model that integrates a carbon budget model. The objective is to maximize the net present value of revenues generated by both the adoption of carbon incentive mechanisms and the sales of

fiber derived from the forest less harvest and regeneration costs. Harvested locations are determined based on economic value of the wood, taking into consideration carbon incentive mechanisms.

Model Formulation

Objective Function:

$$\max_{H^{m'}_{jmcnt}, Y_{hit}} \sum_{hit} \beta^t Y_{hit} R_{it} + \sum_{ii't} \beta^t W_{ii't} \left(R^c_{i't} - C^{tsp}_{ii'}\right) + \sum_{jctmnn'} \beta^t \left(C^h_{jmnt} + C^r_{jm}\right) \sum_h V_{jhmn} H^{m'}_{jmcnt} + \sum_{jmcn} E_{jmcn} X_{jmcnt}$$

$$+ \sum_t \beta^t P_t \left(Z^f_t + Z^p_t - Z^f_{t-1} - Z^p_{t-1}\right) \qquad (3.1)$$

s.t.

Forest Dynamics Constraints:

X_{jmcn0} is given $\forall jmcn$ (3.2)

$$X_{jmcnt+1} = X_{jmcnt}(1-\delta) - \sum_{m'} H^{m'}_{jmcnt} \quad \forall jmcnt \qquad (3.3)$$

$$X_{jmc,1,t+1} = \sum_{c'nm'} H^{m}_{jm'c'nt} \alpha^{cm}_{jnc'm'} \quad \forall jct,\ m=2,3,4 \qquad (3.4)$$

$$X_{jmc,1,t+1} = \sum_{c'nm'} X_{jm'c'nt} \alpha^{cm}_{jnc'm'} \delta \quad \forall jct,\ m=1 \qquad (3.5)$$

Market Clearing and Market Capacity Constraints

$$Y_{hit} = \sum_{jmm'cn} H^{m'}_{jmcnt} V_{jhmn} \quad \forall hit \qquad (3.6)$$

$$W_{ii't} = \sum_{hi'} \theta_{hi} Y_{hit} \qquad \forall it \qquad (3.7)$$

$$\sum_{his} Y_{his} + \sum_{i'} W_{i'it} \leq M_{it} \qquad \forall it \qquad (3.8)$$

Carbon Account Equations

$$Z_t^f = \sum_{pmjcn} C_{pmjcn} X_{jmcnt} \qquad \forall pmjcn \qquad (3.9)$$

$$Z_t^p = \sum_{s\leq t} \sum_{hki} \pi_{hkis} Y_{his} \rho_{kst} + \sum_{s\leq t} \left(\sum_{s<s'\leq t} \sum_{hki} \pi_{hkis} Y_{his} (\rho_{ks'-1t} - \rho_{ks't}) \phi_{k,4} \rho_{4,s't} + \sum_{hki} \pi_{hkis} Y_{his} (1 - \rho_{kss}) \phi_{k,4} \rho_{4,ss} \right)$$

$$+ \sum_{s\leq t} \sum_{kil} \pi_{kil's} W_{ii't} \rho_{kst} + \sum_{s\leq t} \left(\sum_{s<s'\leq t} \sum_{kil'} \pi_{kil's} W_{ii't} (\rho_{ks'-1t} - \rho_{ks't}) \phi_{k,4} \rho_{4,s't} + \sum_{kil'} \pi_{kil's} W_{ii't} (1 - \rho_{kss}) \phi_{k,4} \rho_{4,ss} \right)$$

k summed over 1,2,3. (3.10)

Regulation Constraints

$$\sum_{his} Y_{his} \geq \lambda AC_t \qquad (3.11)$$

$$H^1_{jmcnt} = 0 \qquad (3.12)$$

Definitions of indexes

j=1,…,J An index over yield(or species groups), site classes, and supply locations.

h	Index over two types of wood: softwood or hardwood.
m	Management regime: fire(m=1),extensive(m=2), basic(m=3), or intensive(m=4).
i	Mill locations: sawmill, pulpmill; hardwood export mill; and sawmill quota
s,t=0,..,T	Time period
n	Stand age: 0,...340.
p	Carbon pool: soil, merchantable, below ground, and above ground.
c	Carbon class: 1,2,3 and 4
k	final product carbon pool: construction lumber(k=1), other lumber (k=2), pulp and paper (k=3), landfills (k=4)

Definition of Parameters

β	Discount rate $\beta=1/(1+r)^{10}$
R_{it}	Mill revenue per cubic meter of wood input for the ith mill in period t (includes transport cost).
R_{it}^{c}	Mill revenue per cubic meter of wood chip input for the ith mill in period t.
C_{jmnt}^{h}	Harvest cost per cubic meter for yield group j, management regime m, at age n, period t.
M_{it}	Mill capacity for the ith mill in period t.
AC_t	Allowable cut at period t.
λ	Minimum percentage of allowable cut that is acceptable to harvest.
P_t	Price of carbon in period t.
A_{jcmn}	Area of forest in ha at the beginning of the planning horizon in stand type j, carbon class c, management type m and initial age n.
V_{jhmn}	Volume per hectare of wood in stand type j, species h, management regime m at age n.

C_{pmjcn} Carbon stock in tons per hectare in carbon pool p, for management class m, yield group j, carbon class c, at age n.

$\alpha_{jncm}^{c'm'}$ The portion of yield group j at age n in carbon class c and management type m that ends up in carbon class c', when management regime m' is applied.

C_{jm}^{r} Regeneration cost for management regime m in yield group j.\

C_{ik}^{tsp} Transshipment cost for wood chips from market i to market k.

E_{jmcn} Ending inventory value in $/ha for yield group j under management type m, carbon class c at age n.

δ Natural Disturbance rate

θ_{hi} The proportion of roundwood that is converted to wood chips at market location i for species group h.

π_{hkis} A factor describing how much carbon in metric tons is diverted to carbon product pool k (k=1,2 or 3) from roundwood in m3 of type h, delivered to market i in period s.

ρ_{kst} The proportion of carbon remaining in carbon product pool k at time t for carbon that first entered the pool in time s.

$\phi_{k,4}$ Proportion of carbon from carbon product pool k (k=1,2,3) that enters carbon pool 4 (the landfill) after it is removed from the carbon product pool.

Definition of variables

V_0 Net present value of timber and carbon flows

X_{jmcnt} The area of forest in ha for yield group j, management type m, carbon class c, age n in period t.

$H_{jmcnt}^{m'}$ The area of forest in ha harvested in yield group j, management type m, carbon class c, age n, in period t, that is transferred to management type m' in period $t+1$.

Y_{hit} The volume of wood in m3 of type h delivered to market i in period t.

$W_{ii't}$	The amount of chips in m3 shipped from market i to market i' in period t.
Z_t^f	Forest carbon stocks in pool p at time t.
Z_t^p	Forest product carbon stocks in pool p at time t.

The first equation of the model, Equation 3.1, is the objective function of the firm, which maximizes the net present value of the forest. NPV is equal to the discounted revenue from the sale of wood products and carbon benefits minus the costs associated with the harvest of the wood and manufacturing of forest products.

Equations 3.2 through 3.5 summarize the forest dynamic constraints included in this model. Equation 3.2 states the area of forest yield j, management type m, carbon class c, and age class n in period T0 is given. Equation 3.3 states that in period 2 the area of forest, of a given yield type j, management type m, carbon class c, and age class $n+1$is equal to the area of forest in period one of the same yield type, management type, carbon class, and age class n not disturbed by a natural disturbance or harvested . Equation 3.4 states that the area of forest of a given yield type, management type, carbon class, present in period T+1 of age class 1, is equal to the sum of the area harvested of that yield type, management type and carbon class multiplied by a factor which proportionately transfers land into the two closes carbon classes after a disturbance. Similar to equation 3.4, equation 3.5 proportionately transfers an area that is disturbed by fire into the two closest carbon classes into the first age class.

It is important to discuss carbon classes because it is difficult to model carbon dynamics over time. Carbon stocks in the soils depend on the frequency of harvest and

thus different post-harvest and post fire carbon stocks will result for different ages of disturbance. This means that land that is harvested will not return to the original initial carbon stock from whence it came. There is a great potential for the model size to become unwieldy because the number of post disturbance carbon states is potentially enormous. Hence, a simplified approach to reducing the model size was taken. The approach taken in this project was to set up three carbon classes for each yield and site class group , each representing different initial carbon stock levels from low to high. Land was then transferred into each of these classes from harvested or naturally disturbed stands according to a distribution rule described below. The three carbon classes were determined using the techniques outlined below .

Figure 3-1 illustrates the transfer of land into the three carbon classes after harvest. This figure illustrates how the land of a fire origin pine stand, on a good site, with an initial carbon class of 2 is transferred among carbon classes after harvest when harvested at age 90. After harvest at the age of 90, there are 91.6 tonnes of carbon per hectare. This carbon is transferred into the low carbon class (0 tonnes/ha) and the medium carbon class (178.3 tonnes/ha) by proportionately transferring 49% and 51% into the low and medium carbon classes respectively.

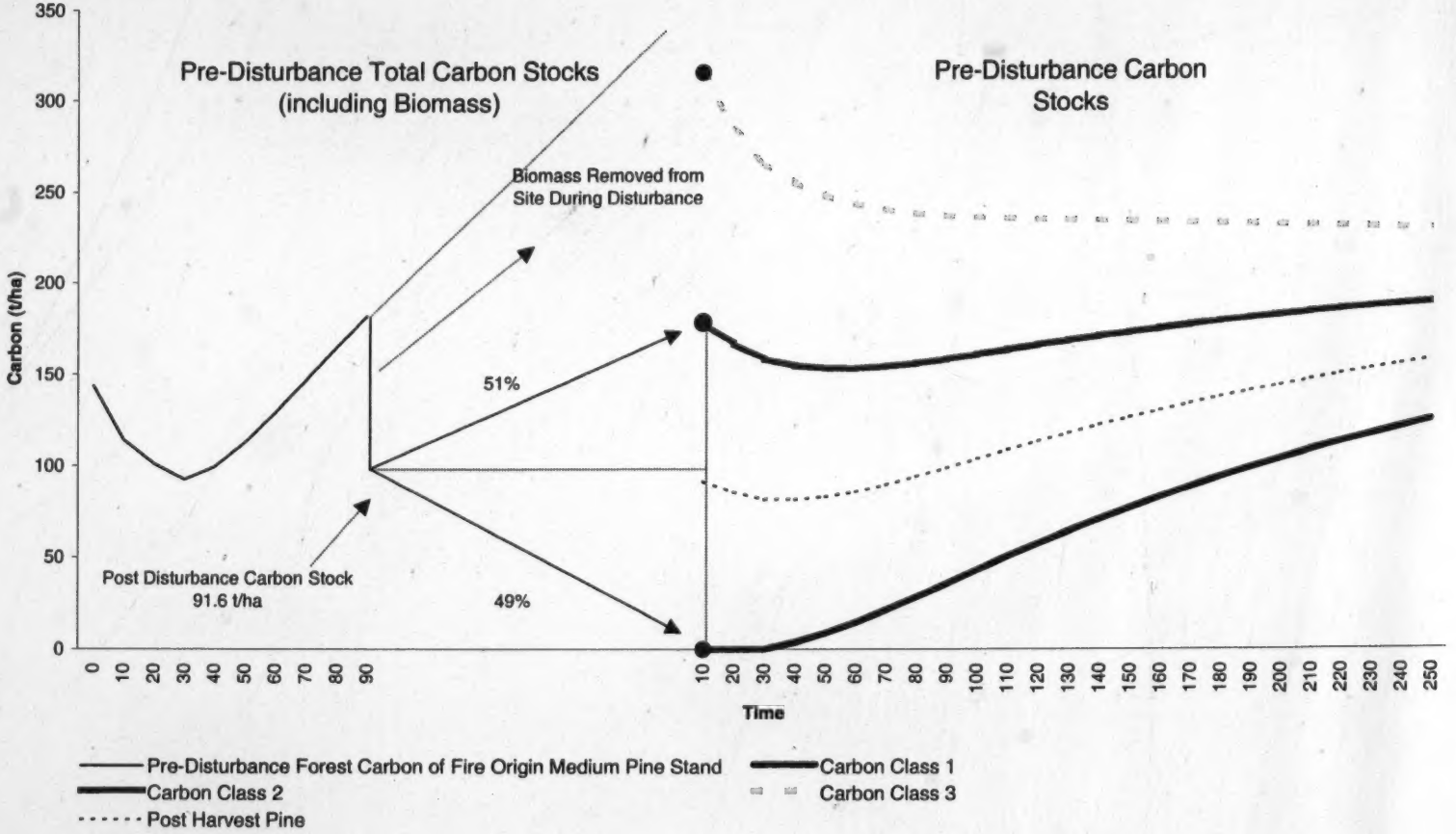
Equations 3.6 through 3.8 represent the market clearing and market capacity constraints included in this model. Equation 3.6 states that the volume of wood delivered in period 1 is equal to the sum of the total area harvested multiplied by volume per hectare. Equation 3.7 states that the volume of chips delivered in period 1 is equal to the

volume of wood harvested multiplied by the proportion of wood that is turned into chips. Equation 3.8 states that the sum of wood and chips delivered cannot exceed the mill capacity.

Equations 3.9 and 3.10 represent the carbon accounting equations included in this model. Equation 3.9 states that forest carbon stocks in pool p are equal to the sum of carbon stocks per hectare in pool p multiplied by the area. Equation 3.10 summarizes the relationship between stock and flows in carbon pools and accounts for the stock of carbon in forest products and the flow of carbon into landfill pools due to the decay of products.

The final two equations included in this model, equations 3.11 and 3.12, summarize the regulatory constraints imposed in this model. Equation 3.11 restricts the volume harvested to be greater than the minimum Annual Allowable Cut (AAC). Equation 3.12 states that an area that is burned cannot be harvested and thus has a harvest level of zero.

Figure 3-1 Carbon Transfer After Harvest



The forest products sector is included in the model in the objective function. Carbon accounting variables (p) are included to measure carbon in the various components of the ecosystem. Both final products (Pulp, Lumber, OSB) and bi-products (pulp, other lumber, construction lumber, chips, bio-energy and waste) are accounted for. Forest product carbon pools (k - construction lumber, other lumber, pulp and paper, and landfill) are also modeled and allows for the tracking of carbon in forest products over time in equation 3.10.

The model scenarios are designed to estimate the carbon supply under different constraints where carbon supply is the quantity of carbon sequestered relative to a baseline. Constraints modeled include both regulatory constraints and carbon accounting constraints. Changing P_t in equation 3.1 changes the carbon price. Even flow regulations were modeled by equation 3.11, which restricts harvest to levels within 5% of AAC, and regeneration constraints were modeled by restricting the model to regenerate by wither basic or intensive methods of regeneration. Carbon accounting stances were modeled by applying carbon prices to various carbon pools as appropriate where a carbon accounting stance is defined as a collection of carbon pools that have incentives placed on them. For example, if only above ground carbon is modeled, than a carbon price is applied to the carbon contained in above ground biomass in equation 3.1. Pools that are not modeled have a carbon price of zero and therefore do not enter equation 3.1. Carbon accounting stances included in this project are described in detail in Chapter 5.

As stated, the model is used to develop 'quasi' carbon supply curves, and not true supply curves. Hence when carbon price is increased in the model simulations, they are changed for each period in the planning horizon. The model was run at various carbon prices ranging from 0 Canadian Dollars per tonne ($/t) to 200 $/t. The carbon accounting system allowed carbon to be tracked during the model horizon and later plotted to determine the amount of carbon supplied at various carbon prices. The amount of carbon supplied at various prices is directly linked to the management of the landscape. It is the management of the landscape, including harvest schedules and regeneration prescriptions that allows the model to generate varying amounts of carbon at various prices. As carbon prices increase, it is more profitable to invest in management practices that sequester carbon than management practices which are aimed at fibre production.

The model was programmed using the program General Algebraic Modeling System (GAMS). This program was chosen due to the ease of changing model specifications in addition to allowing unambiguous statements of algebraic relationships.

3.2 Summary

This chapter presented the formulation of the model used in this project. Chapter 4 describes how the parameters in the model were calibrated.

Chapter 4: Model Calibration

The following chapter summarizes the methods and data used to calibrate the integrated forest management scheduling and carbon budget model described in chapter 3. The objective was to estimate the carbon supply-timber supply relationships for the Weldwood Hinton Inc. FMA area. Model parameters and assumptions are described in the first section while the second section summarizes the forest inventory and includes a discussion of data obtained from Weldwood Inc. The third section describes the yield curve development and aggregation. The fourth section describes the Carbon Budget Model while the fifth section provides a summary of the chapter.

4.1 Data and Calibration

The parameters used in this model were derived from many different sources. The age class distribution (parameter X_{ijcno} in equation 3.2) and volume parameters (V_{jnmn} in equation 3.6) described in the model outlined in chapter 3 were obtained from Weldwood Hinton Inc. Mill capacity (M_{it}) and AAC (AC_t) were also obtained from the firm. Simulations using the methodology of Kurz *et al.* (1992) were used to derive additional parameters including carbon stocks per ha (C_{pmjcn}) and the transfers between carbon classes after disturbances ($\alpha_{jncm}^{c^1 m^1}$). More details on these transfers between carbon classes after disturbances is provided in section 3.1. Additional parameters such as the mill revenue for wood (R_{it} and R_{it}^{c}) and chips, harvest cost (C_{jmnt}^{h}), regeneration costs (C_{jm}^{r}), and transshipment costs (C_{ik}^{tsp}) were obtained from current market data. The data used to calibrate these parameters are described in more detail below.

Model Assumptions

The model was designed with the following assumptions:

1. A planning horizon of 100 years with 10 year planning periods.
2. Four possible stand origins (index m) include fire – natural disturbance, basic – current regeneration practices, extensive – no silviculture after harvest, and intensive – intensive silviculture.[10]
3. Regeneration costs (C^r_{jm}) were included in the model. Regeneration costs were assumed to be \$1180/ha for the 'basic' regeneration and \$1580/ha for 'intensive' regeneration. There were no regeneration costs associated with the extensive management option or the fire disturbances option.
4. Harvest costs (C^h_{jmni}) were incorporated into the model as dollar per cubic meter values and were a function of age. The function contained two components. First a minimum dollars per cubic meter harvest cost was established by computing average harvest costs from Statistics Canada data in \$/m^3 terms. This was obtained by taking the total logging costs and dividing it by total wood harvested in Alberta. The second component was a cost per hectare figure that was obtained by taking the total logging cost and dividing it by the area harvested in Alberta. This was then converted into a cost per cubic meter figure by dividing the \$/ha figure by the volume in m^3/ha for each yield curve. Since the volumes in each yield curve generally increase with age the cost per cubic meter computed this way decreased with age. The final \$/m^3 stand age relationship used in the model was computed by taking the maximum of the cost per cubic meter calculated by the two methods at each age. Harvest costs were calculated like this to account

for the high costs of harvesting both young and overmature stands. Principal statistics necessary for these calculations were obtained from Statistics Canada (1961-1997) logging Catalogue #25-201, and CANSIM matrix 11003 and the National Forestry Database[11]

5. Transport costs (C_{ik}^{tsp}) varied across location and markets and are included in table 4.1 below. These costs were simply based on an assumption that outside mills are at least 50 km away from the forest area and that it costs $0.05 per km to ship a cubic meter of wood.

Table 4-1 Transportation Costs Associated with Harvesting Specific Types of Logs From Supply Locations Given in $/ha

	SW Saw Logs	SW Pulp Logs	HW Pulp Logs	SW SawLogs Out
South	0	0	0	2.5
North	0	0	0	2.5

6. There were three possible uses for wood in the model – softwood saw logs, softwood pulp logs and hardwood pulp logs.
7. Products included in this model include final products including pulp, construction lumber, other lumber and by-products such as chips, bio-energy, waste and emissions. The products and bi-products are calculated (equation 3.9) by assuming a proportion of the input yields the products and bi-products. The proportions are summarized in the following table.

[10] Only MC and Pi include intensive management options.

Table 4-2 Proportion of Inputs Transferred to Product and Bi-Products

	Pulp	Bio-energy	Emissions	Waste	Construction Lumber	Other Lumber	Chips
Softwood Pulp logs	0.425	0	0.1	0.475	-	-	-
Softwood Saw logs	-	-	0.2475	-	0.37	0.135	0.2475
Hardwood Pulp Logs	0.7225	-	0.134	0.114	-	-	-

8. Land classes (indexed by *j* in last chapter) and the initial age distribution (X_{jmcn0}) were obtained using forest inventory data from Weldwood Inc. The inventory data utilized in the model consists of five land classes based on species groupings aspen-hardwood (AW), other hardwoods (OH), mixed conifer (MC), pine (PI) and black spruce (SB). Age classes start at 0-10 and go to a maximum of 250 in 10 year intervals. Site productivity classes (*c*) were available for Mixed Conifer and Pine species groups only. The remainder of the species groups included were assumed to have a medium or '*m*' site class. A summary of the age class distribution for the FMA by yield group, site class, and separated into its North and South components, is included in the Appendix 1. The initial age class distributions presented in Appendix 1 is included in the model via equation 3.2, which simply says X_{jmcn0} is given.

9. Timber net merchantable volumes per ha (V_{jhmn}) were obtained from Weldwood, Inc. Timber volumes provided by Weldwood were not immediately usable because the land classes in the age class distribution represent aggregations of different yield strata therefore it was necessary to modify this data. The final

11 Statistics Canada Logging Catalogue # 25-201, various years from 1961- 1997 can be found at: http://nfdp.ccfm.org/.

timber volumes by land class that were used in this model were weighted averages of more detailed yield strata than were used in this model. Procedures for aggregating yield curves are discussed in section 4.2.

10. Carbon stocks are separated into carbon pools including above ground biomass, below ground biomass, soil biomass and biomass present in the merchantable component of the tree. Collectively these pools are referred to as carbon stocks. Carbon stocks per ha (C_{pmjcn}) were computed using procedures based on the work of Kurz *et al.* (1992) and (1997) discussed in detail in section 4.4.
11. A disturbance rate (δ) of 3.5% over ten years (0.35% annual rate) was applied against each specific land class (X_{jmcni} - species, site class, carbon class, age, and management type combinations) in the model to account for natural disturbances such as fire and insect outbreaks. The disturbance rate of 0.35% was estimated from the history of forest fires for the province of Alberta as an average using data from the Compendium of Canadian Forestry Statistics (CCFM, 2002).
12. Assumed mill prices (R_{it}^c and R_{it}), mill capacities (MC_{it}) and discount rate (β) are included in table 4-3. The mill prices are derived from a number of Statistics Canada sources. The sawmill mill prices are derived from softwood wood input costs, prices and input quantities obtained from Statistics Canada Catalogue 25-250 for years 1985-1995. These data were Alberta based. The price series was extended to 2001 by using national softwood log price indexes obtained from CANSIM time series P6553. The series was then converted to 2001 dollars by using the industrial product price index. The final mill price used in the model is based on a 10-year average of softwood roundwood prices from 1991 to 2001.

The hardwood price was obtained in the same manner except that CANSIM time series P6551 was used to extend the time series. The pulp mill prices are derived from pulpwood input costs and pulpwood input quantities obtained from Statistics Canada Catalogue 36-250XPB Paper and Allied Industries for years 1985-1995. These data were based on all provinces outside Ontario, Quebec and BC. The series was extended to 2001 by using national pulpwood log price indexes obtained from CANSIM time series P6554. The series was then converted to 2001 dollars by using the industrial product price index. The final mill price used in the model is based on a 10-year average of pulpwood prices from 1991-2001. The wood chip price was obtained using the same sources and methods as the pulpwood mill price.

Table 4-3. Mill Price and Mill Capacity Parameter Assumptions

Assumption	Parameter values
Discount rate	.04
Sawmill #1 Mill Price	43.00 ($/m3)
Pulpmill #2 Mill Price	33.50 ($/m3)
Hardwood Export Mill #3 Price	33.50 ($/m3)
Sawmill #4 Mill Price	43.00 ($/m3)
Pulpmill #2 Chips Price	36.00 ($/m3)
Hardwood Export Mill #3 Chip Price	36.00 ($/m3)
Sawmill #1 Capacity	1000000 per annum
Pulpmill #2 Capacity	600000 per annum
Hardwood Export Mill #3 Quota (or share of AAC)	200000 per annum
Sawmill #4 Quota	400000 per annum

13. Mill capacity data was obtained by personal communication with Hugh Lougheed of Weldwood Inc. Mill capacities correspond well with the allowable cut for hardwood and softwood on the FMA area. The softwood mill capacities are reflective of the share of the AAC that go to the FMA holder's sawmill, pulpmill and outside sawmill. The hardwood capacity for the outside hardwood pulp mill corresponds to the AAC for hardwood.

4.2 Yield Curve Construction

The five land classes used in the model are aspen-hardwood (AW), other hardwoods (OH), mixed conifer (MC), pine (PI) and black spruce (SB). Each land class, origin (fire, extensive, basic and intensive) and site class (good, medium and fair) combination is associated with a yield curve using data obtained from Weldwood. Details of the yield curve construction process are provided in this section.

Weldwood Data

Yield curves for each land class combination were constructed by taking a weighted average of yield curves for fifteen different yield strata, based on the FMA using data obtained from Weldwood Inc.[12] The initial 15 different strata obtained from Weldwood are summarized in table 4-4 and a discussion of yield strata is included in section 4.3.

Table 4-4 Summary of Individual Yield Groups Obtained from Weldwood Inventory Data

Yield Group
Mixed Spruce
Black Spruce/Larch
Aspen
Other Hardwood
Aspen/Softwood
Other Hardwood/Softwood
Pine
Pine/ Black Spruce
Pine/Fir
Pine/Hardwood
Pine/White Spruce
Spruce/Hardwood
White Spruce/Pine
White Spruce
Fir

[12] Yield strata are based on a more detailed stratification of the forest landbase than land classes.

For each land class, separate yield curves were developed for the two possible disturbances types: harvesting and fire. For the harvesting regime, three regeneration options were included: basic, extensive, and intensive yield curves. The fire origin curves were developed by first building fire origin yield curves for the 15 different strata and combining those curves using a weighted average based on the area of land of each strata. Weightings are summarized in table 4-5.

Table 4-5 Aggregation of Yield Strata into Project Land Classes

	Percentage (%)				
Yield Strata	AW	OH	PI	MC	SB
Other Hardwood	50	0	0	0	0
Aspen	50	0	0	0	0
Black Spruce/Larch	0	0	0	0	50
Pine	0	0	100	0	0
Mixed Spruce	0	0	0	0	50
White Spruce	0	0	0	10	0
Pine/Fir	0	0	0	20	0
Fir	0	0	0	10	0
Aspen/Softwood	0	33	0	0	0
Pine/White Spruce	0	0	0	0	0
White Spruce/ Hardwood	0	33	0	0	0
Hardwood/Softwood	0	33	0	0	0
White Spruce/Pine	0	0	0	20	0
Pine/Black Spruce	0	0	0	20	0
Pine/Hardwood	0	0	0	20	0

Initially, some species yield curves differentiated between natural subregions within the study area. For simplification purposes, it was necessary to eliminate the natural subregion component of the yield curves provided by the company so that there were not separate yield curves for Pine Upper Foothills (UF), Pine Sub-Alpine/Montain (SA/MO) and Pine Lower Foothills (LF) but simply one for "Pine".[13] Yield curves were developed by combining sub regions wherever distinctions were made. Therefore, the

[13] Where no distinction was made, it was assumed to be an even distribution between the species present in the grouping.

pine curve was obtained by averaging the SA/MO, UF and LF natural sub-region curves using weights defined by the proportion of each natural sub-region in the inventory data.[14] These weights are summarized in table 4-6.

Table 4-6 Aggregation of Natural Subregion Distinctions

Yield Group	Natural Subregion	Proportion (%)	New Yield Group
Pine	SA/MO	16	Pine
	UF	66	
	LF	18	
Pine/Hardwood	LF	46	Pine/Hardwood
	SA/UF	54	

As suggested above, three sets of regenerated yield curves were developed to represent three levels of regeneration management intensity: extensive, basic and intensive. The basic regeneration yield curves were developed to represent the current regeneration standards used by the firm on the FMA area. These regeneration curves, called 'basic', are assumed to be the result of standard management practices including initial site preparation and planting and involve a treatment cost of $1180/ha.[15] The extensive regenerated yield curves were developed to represent a stand that is not actively managed after regeneration therefore a lower yield is expected and thus these curves were derived by taking 60% of the fire origin curves. There was no cost associated with this form of regeneration. The intensive regenerated yield curves were developed to represent a stand that is actively managed after harvest and planting. These curves involved manipulating species composition so that there was 10% more pine present in the stand. It was assumed that this species manipulation could be accomplished using stand

[14] Natural subregions were combined to make a new curve called Pine/Hardwood for both the coniferous and deciduous component of the stand.
[15] Management costs were derived using Canadian national averages of forest management expenditures.

management techniques such as stand tending and result in management costs totaling $1580/ha.

It was also necessary to consider fire origin stands, as a majority of Canada's existing forests are fire origin and because significant portions of forest will continue to be burned in the future. Fire origin yield curves were developed to allow the modeling of carbon levels of fire origin stands and modeling of post fire carbon levels. Further detail on yield curve development is included in section 4.3.

Both coniferous and deciduous components of the stand were modeled to determine the total carbon budget of each type of forest stand. Separate yield curves were developed for coniferous and deciduous components of each yield group based on information provided by the firm's 1999 Forest Management Plan (FMP). Inputs of yield curves included parameters, age and site indices. The coniferous components were straightforward volume accumulation however the deciduous component was modified to allow for decay where decay. Fire and extensive origin Pine, Mixed Conifer and Black Spruce subgroups were comprised of only coniferous yield curves. Aspen-hardwood and Mixed Hardwoods were comprised of both coniferous and deciduous yield curves. Basic and intensive management options comprised both a coniferous component and a deciduous component. A detailed discussion of fire origin, basic, intensive and extensive yield curves is included in the following section.

4.3 Yield Curves Details

A total of 33 different yield groupings, based on origin and land class were formed.[16] A summary of final yield curves developed for this project is included in table 4-7. This table illustrates the curves developed for the various species groups and site classes (j) and management option (m) presented. The development of these curves is summarized below.

Table 4-7 Summary of Final Yield Curve Development

YIELD GROUPING	SITE CLASS	FIRE	EXTENSIVE	BASIC	INTENSIVE
	F				
AW	M	√	√	√	
	G				
	F	√	√	√	√
MC	M	√	√	√	√
	G	√	√	√	√
	F	√	√	√	√
PI	M	√	√	√	√
	G	√	√	√	√
	F				
SB	M	√	√	√	
	G				
	F				
OH	M	√	√	√	
	G				

4.3.1 Fire Origin Yield Curves

Fire origin yield curves were developed using a weighted average of the firms yield strata as described above and shown in table 4-5. Fire origin yield curves were developed using data and functional forms obtained from the firm (Weldwood, 2000). The functional form of yield curves obtained from the firm used site index and start age as parameters, with net merchantable volume as the dependent variable. Both site index

[16] Coniferous and deciduous yield curves were developed where they were required for each of the 33 groupings.

and start age increase the net merchantable volume. Start age increases net merchantable volume by shifting yield curves to the left in this functional form. The site indices and start ages, obtained from the 1999 FMP, and used in the formation of fire origin yield curves are outlined in the table 4-8.[17]

Table 4-8 Site Index and Start Age of Fire Origin Yield Curves

		Good		Medium		Fair	
		Site Index	Start Age	Site Index	Start Age	Site Index	Start Age
AW	Coniferous	19.7	21	16.2	29	12.6	29
	Deciduous	19.7	21	16.2	29	12.6	29
MC	Coniferous	18.2	27	11.6	47	9.58	54
	Deciduous	18.2	27	13.6	47	9.58	54
PI	Coniferous	10.2	23	14.2	32	17.9	48
	Deciduous	-	-	-	-	-	-
SB	Coniferous	13.3	39	8.6	68	8.6	85
	Deciduous	-	-	-	-	-	-
OH	Coniferous	19.8	24	15.1	35	11.3	41
	Deciduous	19.8	24	15.1	35	11.3	41

4.3.2 Extensive Yield Curves

Extensive yield curves were developed using the same species composition, site index and start age as the fire origin curves, where start age is the age at which a tree begins accumulating volume. Extensive curves were 60% of the volume of fire origin curves and were obtained by multiplying fire origin volumes by 0.6.

4.3.3 Basic Yield Curves

The development of the 'basic' yield curves was based on the assumptions found in the firms 1999 FMP. Basic forest management was assumed to alter the species composition of each yield strata and in some cases site index of stands relative to the

[17] Start age is a term used to define the age at which a stand begins accumulating volume.

natural fire origin stands. Site index and start age obtained from the 1999 FMP used to develop basic regeneration yield curves are summarized in table 4-9. The resulting new yield strata were combined into the final 5 yield groups (AW, OH, MC, PI and SB) using a weighted average based on inventory data. The species compositions of the basic yield strata are included in table 4-10.

Table 4-9 Site Index and Start Age of Basic Yield Curves

		Good		Medium		Fair	
		Site Index	Start Age	Site Index	Start Age	Site Index	Start Age
AW	Coniferous	19.3	21	15.8	21	12.2	21
	Deciduous	19.3	21	15.8	21	12.2	21
MC	Coniferous	19.6	21	15.7	24	13.4	35
	Deciduous	18.3	21	13.8	17	12.8	17
PI	Coniferous	13.4	22	17.5	26	21.2	26
	Deciduous	13.4	22	17.5	28	21.2	21
SB	Coniferous	10.0	24	17.0	25	11.8	27
	Deciduous	19.3	21	15.8	21	12.2	21
OH	Coniferous	19.5	16	16.5	19	11.8	21
	Deciduous	19.5	15	16.5	15	12.7	20

Table 4-10 Individual Yield Strata Transitions For Basic Management

Yield Group	%	
Mixed Spruce	70	Pine
	10	Aspen/Softwood
	10	Pine/Black Spruce
	10	White Spruce
Black Spruce/Larch	50	Pine
	30	Pine/Black Spruce
	20	White Spruce
Aspen	100	Aspen
Other Hardwood	100	Other Hardwood
Aspen/Softwood	100	Aspen/Softwood
Other Hardwood/Softwood	100	Other Hardwood/Softwood
Pine	70	Pine
	20	Pine/Hardwood
	10	Aspen/Softwood
Pine/ Black Spruce	50	Pine
	50	Pine/ Black Spruce
Pine/Fir	75	Pine/Fir
	25	Pine
Pine/Hardwood	40	Other Hardwood/Softwood
	30	Aspen/Softwood
	20	Pine/Hardwood
	10	Spruce/Hardwood
Pine/White Spruce	60	Pine
	30	Pine/Fir
	10	Aspen/Softwood
Spruce/Hardwood	75	Spruce/Hardwood
	25	Pine
White Spruce/Pine	60	Pine
	20	Pine/White Spruce
	20	Spruce/Hardwood
White Spruce	40	White Spruce
	40	Pine
	10	Pine/Fir
	10	Spruce/Hardwood
Fir	80	Pine
	20	Mixed Spruce

4.3.4 Intensive Management Yield Curves

Intensive management curves were developed for G, M, and F site classes for only the MC and PI yield groups. These curves were developed on the basis that intensive management translated into a desire to increase fiber and carbon production. Therefore curves were developed by increasing the pine component of each of the yield groups. Intensive yield curves were developed using the site indices and start ages used in the development of the basic curves. Pine components were increased by 10% to represent the increase in pine fiber relative to all other species. Changes in species composition are included in table 4-11.

Table 4-11 Individual Yield Strata Transitions From Basic to Intensive Management

	Percentage (%)			
Yield Strata	PI	MC – Fair	MC – Medium	MC – Good
Pine	90	51	47	36
Mixed Spruce	0	2	2	2
White Spruce	0	4	5	3
Pine/Fir	0	4	6	6
Spruce/ Hardwood	0	1	1	1
Aspen/Softwood	10	0	0	0
Pine/White Spruce	0	4	6	7
White Spruce/ Hardwood	0	4	7	10
Hardwood/Softwood	0	1	5	14
Aspen/Softwood	0	1	4	10
Pine/Black Spruce	0	28	13	4
Pine/Hardwood	0	1	3	7

4.4 The Canadian Forest Carbon Budget Model

Using the work of previous authors including Kurz *et al.* (1992 and 1999) it was possible to design a carbon budget model of the firms FMA. This section describes both the design of the carbon budget model as well as the methodology used to determine

some of the parameters described in section 3.1. The section begins with a summary of three previous studies used as a basis for this study and then proceeds to detail how the Carbon Budget Model was adopted for use in this study. This section provides a description of the simulations used in determining some of the parameters used in the model and includes a discussion of the spreadsheet version of a carbon budget model used in this study. Simulations obtained from this carbon budget model used to determine parameters used in the linear programming (LP) model are also described in the following section.

4.4.1 Introduction to the Carbon Budget Model of the Canadian Forest Sector

The carbon budget parameters (C_{pmjcn} and $\alpha_{jncm}^{c'm'}$) in the linear programming model, outlined in section 3, were derived based on the forest carbon budget model outlined in Kurz *et al.* 1992 and Kurz *et al.* 1999.

Kurz *et al.* (1992) examined the total carbon flux of Canadian forest ecosystems accounting for all forest carbon pools under forest management. The carbon budget model, a computer model developed using published information, was used to determine whether the Canadian forest sector was a net source or a net sink of atmospheric carbon. The Canadian Forest Carbon Budget model tracks carbon in above- and belowground biomass, soils and carbon exchanges among these reservoirs, and the atmosphere. The model also simulates natural growth, mortality, and decomposition processes, and examines the effects of natural disturbances such as fires, and human activities such as harvesting on the forest carbon cycle (Kurz *et al.* 1992).

In 1999, Kurz *et al.* estimated net forest ecosystem carbon fluxes in Canada's 404 Mha of forest between the periods 1920-1989. They concluded that Canada's forests, which are now dominated by mature and overmature trees, are at best carbon neutral and may even be a carbon source.[18] Carbon fluxes during the 70-year study period were driven by changes in the disturbance regimes of the forest, which affected the forest age class structure and increased the average forest age. The authors concluded that the final decade of the study exhibited an increase in disturbances; primarily fire and insect induced mortality, and resulted in a large reduction of ecosystem carbon storage. The previous two studies discussed address carbon stored in the forest however the carbon budget model can be extended to examine the inclusion of carbon in forest products.

Apps *et al.* (1999) extend the carbon budget model to account for carbon in harvested forest biomass, from the time it enters the manufacturing process until it is released into the atmosphere, to examine the role of carbon stored in forest products. The model accounts for the use and production of energy by the forest product sector and emissions of CO_2 during processing. Estimates of changes in the storage of carbon in forest products were also produced. The model allowed the tracking of carbon from transportation of harvested raw materials through the processing in pulp mills or sawmills to it's final destination including short and long lived products as well as landfills. The study concludes that the carbon in the forest product sector is small relative to the forest

[18] Not all forests in Canada are the same and therefore some forests are carbon sinks and others are carbon sources. Current understanding also suggests that Canada's forests fluctuate between being a sink and a source over a period of decades (NRC, 2001).

ecosystem but notes that changes in these carbon stocks contribute significantly to the reduction of total net atmospheric exchange of the total forest sector.

4.4.2 Carbon Budget Model Simulations

In this section, details of how the Canadian Forest Carbon Budget Model was adopted to calibrate parameters used in the linear programming formulation described in Chapter 3 are discussed. Equations and parameters from Kurz *et al.* (1992, 1999) were set up in a spreadsheet application. The resulting spreadsheet version of the carbon budget model allowed for simulated carbon budget responses to alternative harvest ages, timber volume curves linked to alternative silvicultural treatments, and alternative disturbance types (harvest and fire) at the stand level. The basic inputs to the model, discussed in detail below, were the merchantable volume yield curves, discussed in section 4.3, and other parameters taken from Kurz *et al.* (1992) that are applicable to the Foothills model forest area. Stand level carbon budget responses obtained as basic outputs of the model were soil carbon levels, merchantable bole carbon, above ground carbon, and below ground carbon in roots. The ability to track the carbon contained in these forest carbon pools is important as the following chapter analyzes the effects of carbon accounting stance on above ground biomass, below ground biomass and soil carbon.

The basic inputs used to estimate carbon stocks in living biomass were the yield curves for each land class described in the previous section. In addition, to the yield curves, height and diameter at breast height (DBH) curves were used in conjunction with

biomass models, which estimate biomass in the merchantable bole and crown of trees (Singh, 1982).[19] Biomass models were used to compute proportions of above ground carbon that reside in the merchantable bole, branches and foliage (Singh, 1982). The proportions from the biomass models were then used to estimate the carbon in the branches and foliage using the carbon estimate for the merchantable bole as a base. An estimate of below ground biomass was estimated using the models by Kurz *et al.* (1992).

Estimates of biomass in the branches, foliage and roots are important for two reasons. First, for the purposes of estimating total carbon stocks, it is important to know the total living biomass not just the merchantable component. The second reason is that the Carbon Budget Model uses the biomass in each of these components as inputs in computing inputs to soil carbon pools.

Simulations were run to determine the soil biomass resulting from fire origin and 3 regeneration origin stands. These simulations were compiled in a table and read into the GAMS model. The carbon stocks in each component (above ground carbon, below ground and soil carbon) in each land class and age class were used in the integrated forest management scheduling-carbon budget model and appear as the C_{pmjcn} parameter described in chapter 3.

4.4.3 Carbon Budget Model Simulation Methods

In order to estimate the carbon budget, simulations were run to determine the amount of carbon remaining in the stand both before and after a disturbance such as fire

[19] Height and DBH curves were obtained from Alberta Vegetation Index (AVI)

or harvest. These simulations were run for fire origin and 3 regeneration origin stands for all of the site class/land class combinations included in this project. Carbon stocks were modeled in three stages. The three stages of simulations are described in detail below.

The first stage of modeling was to establish the carbon classes. The establishment of carbon classes enabled a discussion of carbon dynamics over time. Further discussion of post disturbance (fire or harvest) carbon levels is included in section 3.1.

To determine carbon classes it was necessary to first estimate the maximum possible soil carbon stock. The minimum was assumed to be zero. These formed two of three possible post-disturbance carbon stock levels used in the model. The third was obtained by taking the midpoint between the maximum and the minimum.

The highest carbon class was assumed to occur at the 340-year harvest and that a middle carbon class was at the halfway point between the minimum and maximum for the coniferous component of the stand. This assumption needed to be modified to accurately represent the deciduous component of the stand. Given the functional form of the deciduous component, described in chapter 2, the maximum biomass, and therefore carbon, did not necessarily occur at the maximum harvest age of 340 years. It was therefore necessary to 'step by step' model these groups to determine the maximum carbon content of the stand and when that maximum was reached. The purpose of obtaining a maximum and minimum was to determine the high and low bounds allowing

for three carbon classes to be determined for the sites included in the model. These values are included in table 4-12.

Table 4-12 Carbon Class Ranges

Land Class	Site Class	Class 1	Class 2	Class 3
AW	Good	0.00	155.14	310.27
	Medium	0.00	128.57	257.14
	Fair	0.00	113.75	227.51
OH	Good	0.00	182.28	364.56
	Medium	0.00	156.25	312.50
	Fair	0.00	138.98	277.95
MC	Good	0.00	275.34	550.67
	Medium	0.00	226.33	452.66
	Fair	0.00	196.16	392.32
PI	Good	0.00	245.93	491.85
	Medium	0.00	207.25	414.49
	Fair	0.00	178.10	356.20
SB	Good	0.00	224.31	448.62
	Medium	0.00	203.61	407.21
	Fair	0.00	168.85	337.70

The second stage of modeling involved simulating pre and post harvest carbon stocks for each stand age and harvest age. Starting carbon levels were determined for each possible age class. This was necessary because starting soil carbon values are dependent on the carbon in the previous period and therefore are dependent on the previous harvest timings. For example, a stand that was harvested at 100 years of age has a different starting value of carbon than a stand that was harvested at 150 years of age. For simplification purposes, four possible post disturbance starting points or states were defined; these were natural fire disturbance levels, zero, a medium level and the maximum carbon level for each yield group-site class combination. Natural fire rotation starting values were determined by simulating repeated consecutive fires every 105 years (natural fire rotation) and replacing starting values with the converged values obtained

after each fire. Long rage fire origin carbon class starting values are summarized in table 4-13.

Table 4-13 Long Run Fire Origin Carbon Class Starting Values

Land Class	Site Class	Fire	Basic	Extensive	Intensive
AW	Good	200.42	205.08	150.79	-
	Medium	166.28	168.31	126.41	-
	Fair	141.37	153.05	107.56	-
OH	Good	195.24	196.42	148.57	-
	Medium	154.94	165.04	119.62	-
	Fair	121.55	145.97	95.02	-
MC	Good	295.36	237.01	216.75	245.18
	Medium	224.41	215.51	166.82	217.81
	Fair	150.31	163.13	86.99	155.47
PI	Good	174.06	296.21	124.22	312.07
	Medium	144.00	250.20	99.01	262.67
	Fair	83.45	217.08	61.39	226.26
SB	Good	70.22	317.21	51.46	-
	Medium	33.40	279.69	23.92	-
	Fair	14.04	231.85	8.91	-

The final stage of simulations involved establishing the transfer parameters by taking post harvest carbon and comparing it to the pre-determined carbon classes. The bounds of the three carbon classes were used to determine how land is transferred between site classes after harvests or fires and was ultimately used to determine a transfer matrix to be used in the GAMS program. The transfer matrix, included in the model as $\alpha_{jncm}^{c'm'}$, was determined by simulating the post harvest carbon at various harvest ages and using the horizontal look-up function in excel to determine what proportion of the carbon remaining after harvest is transferred into the closest 2 carbon classes. Further explanation of this is included in section 3.1 and in figure 3-1. An important observation during the initial simulations of the Carbon Budget Model was that harvest age plays a vital role in the determination the amount of carbon contained in the forest.

4.5 Summary

Prior to the examination of carbon accounting stances it was necessary to develop estimates for the carbon contained in the forest. This was based on the work of Kurz *et al.* (1992) and using inventory data obtained from the firm and AVI. The formation of parameters including estimates of forest carbon is described in this section. In the following chapter, the estimates obtained from the Carbon Budget Model are used to examine the effects of baselines, carbon accounting stance and regulatory regime on forest management. Chapter 5 provides an in-depth analysis of the carbon accounting stances proposed.

Chapter 5: Results

The purpose of this chapter is to address the research objectives outlined in chapter one which include: estimating how optimal forest management should change when a forestry firm is faced with incentives to sequester carbon; estimating carbon credit supply curves under different carbon incentive packages defined by the scope of the carbon accounting system; estimating the effects of carbon incentives on wood supply for timber products; and estimating the effect of forest regulation constraints. This problem is examined using the perspective of a forest products firm that is considering entering into a long-term carbon sequestration contract with a buyer seeking offsets for required emissions reductions.

The first section of Chapter 5 introduces quasi carbon supply curves and provides a brief discussion of three important factors that determine carbon supply. These include carbon accounting stance, regulations and the establishment of baselines. A discussion of the eight model scenarios included in this study is also presented. This section includes a discussion of the scope of carbon incentives relative to what forest carbon pools (above ground, below ground, soil and forest products) are included in the incentive stance as well as the regulatory regime modeled. For the purpose of discussion, these incentive schemes are called "carbon accounting stance". In the second section combined timber and carbon Net Present Value (NPV) results are presented and discussed, followed by a discussion of the NPV of Carbon and proportion of NPV derived from carbon benefits. The third section of this chapter presents the carbon supply, timber supply and harvest/regeneration results of the model scenarios included. This section also provides a

discussion of carbon supply under the carbon accounting stance in both a regulated and unregulated framework. The final section provides concluding remarks.

Quasi-Carbon Supply

The carbon supply computed in this chapter is really not 'supply' as is traditionally meant in economics. Supply generally means the quantity supplied at a given price in a given time period, *ceteris paribus*. However, here, carbon price is simultaneously changed in 10 periods of time and carbon response quantities in a given period are not solely generated by the price change in that given period. Therefore it should be noted that when the words "carbon supply" are used in this study it is not used in the strictest sense. The term "Quasi-carbon supply" might be more appropriate but for brevity's sake the term "carbon supply" is used most often in the remainder of this thesis.

Estimates of carbon supply were obtained from the model under each scenario (discussed in section 5.1) by iteratively re-running the model for a range of carbon prices from zero to $200/t where the carbon price was kept constant over the 10 periods (each 10 years) of the planning horizon. Carbon supply was then calculated by comparing the carbon stocks derived from the model to the carbon stock baseline levels. An in-depth discussion of the establishment of baselines is included in section 5-1.

Carbon supply can be expressed using the following formula: $(C_{t+1}-C_t)-(B_{t+1}-B_t)$ where C_t is the actual carbon level at time *t* and B_t is the baseline carbon level at time t. The method of determining baselines has several implications in the calculation of credits. If the baseline is constant, then the terms in the second set of brackets are always

zero and C_{t+1}-C_t determines the number of carbon credits. In this case the value of carbon credits is $P_{t+1}(C_{t+1}-C_t)$, which will be negative for any decrease in carbon stock and positive for any increase in carbon stock. This setup creates an incentive to both increase the carbon stock trajectories and lessen the decrease of declining carbon stock trajectories. However, if carbon stocks are decreasing at a lesser rate under carbon management than without carbon management, the firm will incur a loss under a constant baseline. Alternatively, if the baseline is increasing, any increases in the carbon stock trajectory over time along the baseline will be partially offset by increases that would have occurred along the baseline. Finally, if the baseline is decreasing, any increases in carbon stock relative to the declining baseline (even if carbon stocks are still decreasing in absolute terms) will generate a positive value of credits. This implies that a firm with declining carbon stocks may not want to participate in a trading structure unless their baseline is also declining. However if declining carbon stocks can be used as the basis of comparison to generate carbon credits, than firms may find it beneficial to participate. In summary, carbon supply varies greatly depending on the chosen baseline.

Carbon Accounting Stance

Carbon accounting stance reflect which carbon pools are actually counted in applying the carbon incentive or carbon price to determine the value of carbon sequestration or loss. Examining carbon supply, under different carbon accounting stances, is important for the following reasons. First, there are many difficulties associated with measuring forest and forest product carbon. These difficulties will present various technological challenges and will likely prove costly. For this reason it is

not certain which carbon pools would actually be included in a carbon incentive package. For example, forest products are not currently included under the Kyoto framework. Second, the inclusion of some carbon pools and not others within a given incentive stance may have a large impact on the total amount of carbon sequestered (in all pools). The potential importance of below ground and soil carbon and forest products can be seen in figure 5-2. This figure illustrates the carbon present in the forest under the BAU scenario in above ground biomass, in all forest carbon pools (forest carbon), and all forest pools plus forest product pools (total carbon). From this figure, the sheer volume of carbon present in the soil and below ground carbon can be seen as the difference between the above ground and forest carbon lines. The uncertainty surrounding the ability to measure soil carbon, combined with the dominance of soil carbon pools in terms of size compared to other pools, means carbon supply under various carbon incentive accounts should be examined.

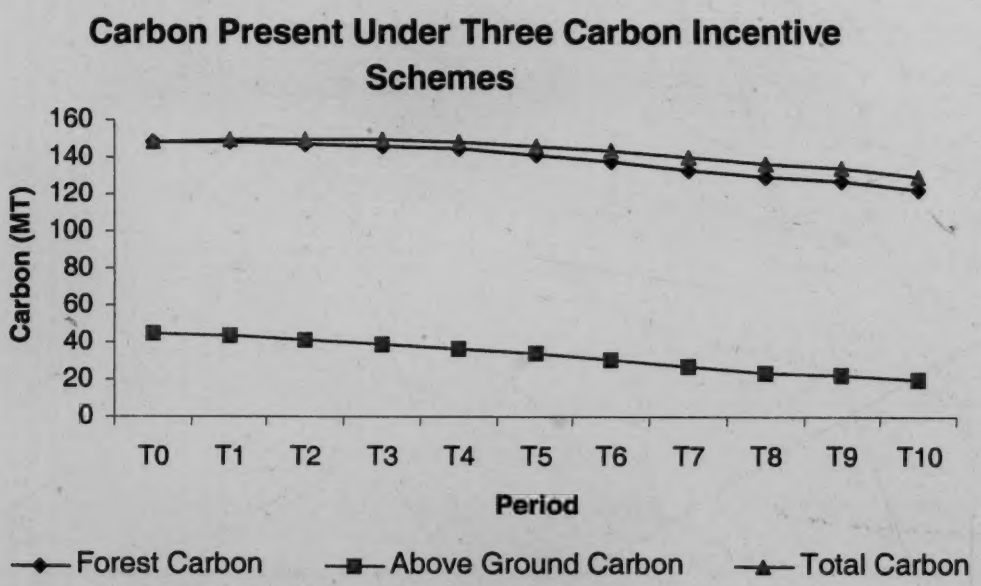


Figure 5-1 Carbon Incentive accounts of BAU Baseline

For these reason, incentive packages were applied to three combinations of components within the complete carbon account to assess the effects of using incomplete accounts on carbon sequestration and supply. The three combinations of components included were: (1) above ground carbon - merchantable and above ground biomass; (2) forest carbon - merchantable, above, below ground biomass and soil carbon; and (3) total carbon which includes total forest carbon and forest products thus providing a complete carbon account. For ease of explanation, these combinations will be referred to as the carbon accounting stance.

Regulatory Regime

The province grants rights to harvest timber to firms through Forest Management Agreements (FMAs). These agreements determine an Annual Allowable Cut (AAC), which restricts the firms harvest levels. These harvest level regulations are modeled in this study as constraints to harvest within 5% of a provincially determined AAC. The AAC levels for softwood and hardwood and the share of the AAC that goes to the FMA holder's sawmill and pulpmill as well as to other mills is reflected in the maximum cut levels shown in table 4.8 in Chapter 4. An additional restriction placed on firms by provincial regulations is a restriction on regeneration practices. Current regulations ensure that upon harvest, forest stands are returned to the same species composition and conditions present prior to harvest. This was modeled as a restriction to choose only basic or intensive management options (regenerations are indexed by m in the model formulation in chapter 3). Both of these restrictions have the potential to limit the ability of a firm to react to carbon incentives.

Carbon Stock Baselines

As mentioned above, establishment of a baseline is vital to the discussion of carbon credits because carbon credit supply is determined relative to a chosen, approved or agreed upon baseline. Once determined, the baseline is fixed and is used to determine whether carbon levels have changed. The combination of baselines and incentives may provide firms with the motivation to increase the carbon stock of the forest. One method that could be used to encourage action by firms is providing incentives on the various carbon pools, as discussed in Chapter 2.

There is currently a lot of uncertainty surrounding what an appropriate baseline is and therefore two are considered in this study. They are a BAU baseline, and a baseline based on initial 2000 carbon stocks level (horizontal baseline). For the purpose of this study, each baseline is calculated via a model run, where 'run' consists of running the model at a specific carbon price. In this case, each baseline calculation consists of 1 run at a carbon price of zero while maximizing the discounted net timber revenues given the existing regulatory regimes. This allows for the tracking of forest carbon stocks and forest products over time. Each baseline run produces estimates of carbon stocks of all pools under one of the three carbon accounting stances. Therefore a total of 6 baselines were produced including a BAU and a horizontal baseline measuring each of the three incentive accounts. For example, the above ground BAU baseline, includes only carbon in the above ground components of the stand; the forest carbon BAU baseline consists of the carbon in all above ground and below ground carbon and soils and the total carbon BAU baseline contains carbon in all the carbon pools. Further discussion of baselines is included in section 5.1.1.

5.1 Model Scenarios

A total of eight model scenarios were developed to examine the impacts of carbon benefits on carbon supply. Table 5-1 summarizes the eight scenarios that examine different combinations of baselines, regulatory regimes and carbon accounting stance and 16 price runs for each scenario. To distinguish between a 'run" and a "scenario" in the rest of this chapter, a 'run' consists of running the model at one price and a 'scenario' is a set of runs with carbon prices of 0-200 $/t. The first 2 scenarios are baselines and provide a projection of carbon over time. As discussed, two baselines are simulated in this study including a BAU and an initial carbon stock levels (or horizontal baseline). Baselines provide an estimate of carbon stocks in each 10-year period broken down by carbon pools, as discussed in Chapter 2 and baselines are discussed further in section 5.1.1. Each baseline is calculated using one run, at a carbon price of zero, and scenarios 3 through 8 involve a set of runs over the 16 carbon prices. Scenarios 3 through 5 are designed to compare carbon supply under different carbon accounting stances. Scenarios 6 through 8 are designed to examine the effects of regulations on forest management.

Table 5-1 Model Scenarios

Scenario Name	Carbon Accounting Incentives	Regulations Maximum Cut	Minimum Cut	Regeneration Restrictions	Carbon Prices $/t
Scenario 1: BAU	Above Ground Above Ground, Below Ground and Soil Above Ground, Below Ground, Soil and Forest Products	Yes	Yes	Yes	N/A
Scenario 2: Horizontal Baseline	Above Ground Above Ground, Below Ground and Soil Above Ground, Below Ground, Soil and Forest Products	N/A	N/A	N/A	N/A
Scenario 3: Above Ground Regulated	Above Ground	Yes	Yes	Yes	1,2,..200
Scenario 4: Forest Carbon Regulated	Above Ground, Below Ground and Soil	Yes	Yes	Yes	1,2,..200
Scenario 5: Total Carbon Regulated	Above Ground, Below Ground, Soil with Forest Products	Yes	Yes	Yes	1,2,..200
Scenario 6: Above Ground Unregulated	Above Ground	Yes	No	No	1,2,..200
Scenario 7: Forest Carbon Unregulated	Above Ground, Below Ground and Soil	Yes	No	No	1,2,..200
Scenario 8: Total Carbon Unregulated	Above Ground, Below Ground, Soil with Forest Products	Yes	No	No	1,2,..200

Summary and Purpose of Model Experiments

Differences in carbon supply under scenarios 3 to 5 were generated by varying the carbon incentive account. Moreover, under these scenarios, carbon supply was influenced by the presence of the regulatory regime. The carbon supply under scenarios 6 to 8 also varied because of the different carbon accounting stance reflected in the respective scenarios. Perhaps a more important comparison, however, is that carbon supply under the 'restricted' regulatory regime of scenarios 3 to 5 should differ from carbon supply under the 'relaxed' regulatory regime of scenarios 6 to 8. The comparison of scenario 3 to 6, 4 to 7 and 5 to 8 allowed for an examination of the impact of the regulatory constraints on carbon supply under different carbon accounting stances.

For model scenarios 3 to 8 there were 16 carbon price runs made, including the zero carbon price. Hence, including the 6 runs made to construct the baseline scenarios a total of 102 model runs were made.

Scenario 1: BAU Baseline

The BAU scenario was derived by setting up the LP model to emulate current forest management practices in terms of harvest rates, upper and lower bounds on harvest rates imposed by the regulatory environment, and constraints on regeneration options chosen. Under the BAU scenario, the optimization model was restricted to the choice of basic or intensive method regeneration options. Non-declining evenflow constraints imposed by the regulatory environment were included in this model by using equation 3.11 to impose an upper bound on harvest (see chapter 4 Table 4.2 for upper bounds) and another equation similar to 3.11 to impose a lower bound on harvest levels. This latter

equation constrained harvest levels to decline at most by 5% of the AAC. The BAU scenario also involved an annual disturbance rate of 3.5% every ten years to simulate long run provincial disturbance averages.

Scenario 2: Initial Carbon Stock Baseline (Horizontal Baseline)

The initial carbon stock baseline is simply the carbon present in 2000 and is constant over time. This baseline is proposed as a means of estimating the carbon stock at the moment a firm enters into a sequestration contract.

Scenarios 1 and 2 produce different results. Figure 5-2 illustrates the 6 baselines used in this study. The BAU baselines of both the above ground scenario and the forest carbon scenario decline over time. The decline in carbon stocks of the BAU baseline may be attributed to the harvest of mature stands and replacement with young stands. The total carbon baseline increases until period T4 and then begins to decline. The increase during early periods is due to the inclusion of carbon in forest products. The decline is due to the decline in forest carbon offsetting the carbon stored in forest products. The year 2000 baselines illustrate the carbon present in the year 2000 and are therefore horizontal.

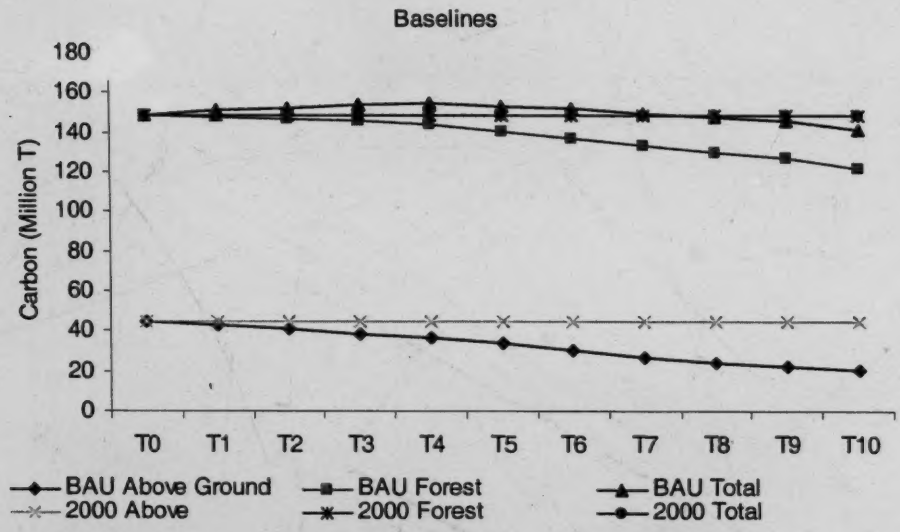


Figure 5-2 **Carbon Contained Carbon Incentive Account Baselines**

Scenarios 3 to 5: Restricted Regulatory Regime under 3 Carbon accounting stances

The next three scenarios, called 'Restricted', examine carbon supply when incentives are applied under three different carbon accounting stances (above ground carbon, forest carbon and total carbon) in a regulated environment. These scenarios are designed to model the current regulatory environment in which harvest levels are restricted to be within some percentage of the calculated annual allowable cut and in which there are regeneration standards which must be upheld by the forestry firm forests in the province.

Scenarios 6 to 8: Relaxed Regulatory Regime under 3 Carbon accounting stances

The final three scenarios are designed to reveal how carbon supply changes, over time, relative to scenarios 3 to 5, when incentives are applied under the three carbon

accounting stances and when regulations are significantly relaxed from the current situation. Relaxation of regulations are modeled in two ways. First, the constraint requiring regeneration choices to be basic and intensive only is relaxed to also allow the extensive management option to be chosen. Second, equation 3.11 is eliminated from the model, which allows harvest levels to fall below the minimum harvest levels imposed by evenflow regulations.

5.2 Results

The objective function value (equation 3.1), in scenarios 3 to 8 is affected by three major factors as described above: the chosen baseline, the carbon accounting stance and the regulatory regime in addition to carbon price. It is therefore important to examine the effects of each of these factors. This section begins with a discussion of the combined timber and carbon NPV of timber and carbon. The NPV of carbon results for all scenarios and baselines and the proportion of NPV derived from carbon benefits are then discussed.

5.2.1 Timber and Carbon NPV Results

The timber and carbon NPV results, are presented in table 5-2 for each model scenario and run. Net present values are presented for both BAU and horizontal baselines. The following section provides a discussion and comparison of the NPV results obtained from the model.

Table 5-2 Combined Timber and Carbon NPV Results

		Restricted			Unrestricted		
	Carbon Price $/t	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
NPV of Timber and Carbon Determined by Horizontal Baseline (millions)	0	1,128.48	1,128.48	1,128.48	1,355.53	1,355.53	1,355.53
	1	1,121.56	1,123.80	1,131.60	1,355.53	1,352.01	1,359.14
	2	1,114.72	1,119.41	1,134.83	1,344.10	1,348.54	1,362.79
	4	1,101.57	1,111.78	1,142.07	1,332.76	1,341.83	1,370.18
	6	1,088.87	1,104.28	1,149.71	1,321.58	1,335.77	1,378.03
	8	1,076.19	1,096.87	1,157.44	1,310.77	1,330.15	1,386.13
	10	1,063.54	1,089.51	1,165.22	1,300.06	1,325.00	1,394.55
	20	1,000.49	1,053.08	1,204.51	1,248.99	1,312.13	1,441.85
	30	937.66	1,017.33	1,244.48	1,205.12	1,322.71	1,497.20
	40	875.01	981.94	1,284.80	1,171.49	1,336.33	1,566.18
	50	812.51	946.71	1,325.29	1,143.17	1,355.99	1,637.27
	60	750.15	911.67	1,365.96	1,115.33	1,397.06	1,712.72
	70	687.94	876.72	1,406.73	1,091.13	1,474.96	1,798.89
	80	625.90	841.81	1,447.53	1,074.96	1,571.03	1,889.69
	90	563.90	807.21	1,488.46	1,064.55	1,687.80	1,988.26
	100	502.04	772.94	1,529.51	1,060.26	1,841.36	2,097.76
	125	347.88	687.65	1,632.36	1,112.14	2,272.81	2,413.22
	150	194.52	603.05	1,735.50	1,301.06	2,708.56	2,761.97
	175	41.64	518.56	1,838.75	1,502.22	3,144.30	3,158.83
	200	(110.86)	434.07	1,942.01	1,703.38	3,580.04	3,583.23
NPV of Timber and Carbon Determined by BAU Baseline (millions)	0	1,128.48	1,128.48	1,128.48	1,355.53	1,355.53	1,355.53
	1	1,128.48	1,128.54	1,128.50	1,362.45	1,356.75	1,356.03
	2	1,128.57	1,128.88	1,128.62	1,357.94	1,358.01	1,356.58
	4	1,129.26	1,130.73	1,129.64	1,360.45	1,360.77	1,357.76
	6	1,130.39	1,132.71	1,131.08	1,363.11	1,364.19	1,359.40
	8	1,131.56	1,134.76	1,132.59	1,366.14	1,368.05	1,361.29
	10	1,132.75	1,136.88	1,134.16	1,369.27	1,372.38	1,363.49
	20	1,138.91	1,147.83	1,142.40	1,387.41	1,406.87	1,379.73
	30	1,145.29	1,159.45	1,151.30	1,412.76	1,464.82	1,404.02
	40	1,151.85	1,171.43	1,160.57	1,448.34	1,525.82	1,441.95
	50	1,158.56	1,183.57	1,169.99	1,489.23	1,592.84	1,481.98
	60	1,165.41	1,195.90	1,179.61	1,530.60	1,681.29	1,526.37
	70	1,172.42	1,208.32	1,189.32	1,575.61	1,806.56	1,581.48
	80	1,179.59	1,220.78	1,199.06	1,628.64	1,950.00	1,641.22
	90	1,186.79	1,233.55	1,208.94	1,687.45	2,114.14	1,708.73
	100	1,194.15	1,246.66	1,218.93	1,752.37	2,315.07	1,787.17
	125	1,213.02	1,279.79	1,244.12	1,977.27	2,864.96	2,024.98
	150	1,232.69	1,313.62	1,269.62	2,339.22	3,419.13	2,296.09
	175	1,252.84	1,347.55	1,295.22	2,713.41	3,973.30	2,615.30
	200	1,273.36	1,381.50	1,320.84	3,087.60	4,527.47	2,962.06

The NPV obtained from the BAU baseline in all scenarios increases as carbon prices rise under the forest carbon accounting stance. The largest NPV obtained in the three regulated scenarios is obtained by scenario 4, the forest carbon account. NPV results obtained from the forest carbon account are larger than the NPV results obtained from total carbon account (Scenario 5). The addition of forest products into the account results in higher NPVs because the loss of carbon due to harvest is not as great as when forest products are not counted. Hence the penalty for harvesting is less, leading to an increase in NPV when forest products are included as compared to the forest carbon account where products are not included. In addition, as seen on figure 5-2 carbon stocks increase initially when products are included. Hence more carbon credits are accumulated relative to the baseline. The smallest NPV's are obtained from above ground carbon account (Scenario 3).

Examination of combined NPVs obtained from the unrestricted model show that in all scenarios, increases in carbon prices result in increases in combined NPVs. The largest NPV obtained in the three unregulated scenarios is obtained by scenario 7 where incentives are on the forest carbon account only. The smallest NPV's are again obtained for scenario 6 (incentives on above ground carbon account only). The addition of forest products to the incentive package (Scenario 8) causes the NPV to be smaller than the scenario where forest products are not counted (forest carbon account). The NPV obtained from the unregulated scenarios are always larger than their corresponding regulated scenarios. For example, when only above ground carbon is counted, relaxing regulatory regimes increases NPV over all prices. This can be seen by comparing

scenarios 3 and 6. This holds true for the other two carbon accounting stances as well which can be seen by comparing 4 and 7 (forest carbon account) and 5 and 8 (including forest products).

Another potential carbon stock baseline that may be relevant is a horizontal baseline. Examining combined NPVs relative to a horizontal baseline shows that the in all cases, the inclusion of additional carbon accounts results in higher NPVs. For example, the highest NPV occurs in the total carbon account scenario (scenario 5), followed by the forest carbon account scenario (scenario 4). The above ground carbon account produces the smallest NPV. An examination of model results shows that above ground and forest carbon accounts produce declining NPV's as carbon prices rise. The declining NPV is due to the conflicting nature of supplying carbon stocks and supplying timber since both carbon stocks and timber supply have value. The inclusion of forest products results in NPVs that increase as carbon prices rise due to the storage of carbon in forest products. When regulations are relaxed, NPV's are larger than when regulations are imposed. For example, the unrestricted forest carbon incentive account is larger than the restricted carbon account. This relationship holds for all carbon accounts.

When the NPV results of the horizontal baselines and BAU baselines are compared, it is clear that the NPV's obtained from a BAU baseline are always larger than those obtained from the horizontal baseline when incentives are placed on above ground carbon (scenarios 3 and 6) and forest carbon (scenario 4 and 7). The increase in NPV is due to the declining carbon stocks in the BAU baseline (see figure 5-2). When incentives

are placed on total forest carbon (scenario 5 and 8), the NPV obtained from a horizontal baseline is greater than the NPV obtained from the BAU baseline. This is again due to the nature of the BAU baseline which increases during the first few planning periods and then decreases, therefore the NPV decreases when products are included in the BAU scenario. These results are expected as the BAU baseline is decreasing over time and the horizontal baseline is not. Therefore, the relative difference between the carbon stocks and the baseline is always larger for the BAU baselines than the horizontal baseline.

5.2.2 Net Present Value of Carbon

Table 5-3 provides a summary of the NPV of carbon in scenarios 3 through 8 at various carbon prices. Examining the NPV of carbon relative to a BAU baseline shows that increases in the carbon price result in increases in the NPV of carbon in all scenarios. The largest NPV is obtained under a forest carbon account, followed by the NPV associated with a total carbon account. The smallest NPV is obtained under an above ground carbon account. In the unrestricted model, the forest carbon incentive account produces the largest NPV, followed by the above ground carbon account, while the total carbon incentive account produces the smallest NPV's. Relaxing regulations results in higher NPVs in all scenarios.

Examining the NPV of carbon relative to a horizontal baseline produces different results. An examination of the NPV of carbon relative to the above ground carbon incentive and the forest carbon account shows that as carbon prices increase, the value of carbon is negative and becomes increasingly negative relative to a horizontal baseline. The inclusion of forest products causes the NPV to increases as carbon prices increase.

When regulations are relaxed, NPVs are positive and increase as carbon prices increase.

Relaxation of regulations results in higher NPVs than when regulations are imposed.

Table 5-3 NPV of Carbon Results

		Restricted			Unrestricted		
	Carbon price $/t	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
NPV of Carbon Determined by Horizontal Baseline (millions)	0	-	-	-	-	-	-
	1	(4.67)	(3.09)	2.18	(3.86)	(2.36)	2.46
	2	(9.23)	(5.47)	4.52	(7.69)	(4.65)	4.94
	4	(17.19)	(10.15)	10.31	(15.29)	(8.36)	10.07
	6	(25.72)	(15.16)	15.53	(22.08)	(12.02)	16.32
	8	(34.20)	(19.90)	21.02	(29.18)	(14.47)	22.16
	10	(42.69)	(24.83)	26.33	(36.04)	(15.42)	29.00
	20	(85.04)	(48.65)	53.65	(65.41)	(1.97)	72.54
	30	(127.29)	(71.91)	81.54	(86.96)	25.18	123.99
	40	(169.10)	(95.35)	109.26	(77.80)	42.32	191.14
	50	(210.83)	(118.52)	137.23	(94.76)	97.49	242.06
	60	(252.63)	(141.78)	165.13	(110.39)	217.79	316.41
	70	(293.50)	(165.24)	192.82	(93.17)	441.23	417.67
	80	(335.23)	(188.19)	221.01	(71.01)	530.66	509.83
	90	(376.23)	(208.63)	249.32	(37.62)	850.31	635.13
	100	(417.68)	(231.23)	277.47	2.49	1,106.17	796.61
	125	(518.58)	(286.22)	347.81	469.57	1,471.86	1,093.15
	150	(621.30)	(342.58)	418.51	815.38	1,766.23	1,519.94
	175	(721.44)	(399.54)	488.29	951.27	2,060.60	1,956.43
	200	(823.94)	(456.53)	558.16	1,087.17	2,354.98	2,327.92
NPV of Carbon Determined by BAU Baseline (millions)	0	-	-	-	-	-	-
	1	0.00	0.11	0.08	0.82	0.84	0.36
	2	0.12	0.93	0.32	1.66	1.75	0.75
	4	1.51	2.65	1.92	3.42	4.44	1.67
	6	2.33	4.04	2.94	5.97	7.18	3.73
	8	3.20	5.70	4.23	8.22	11.13	5.38
	10	4.07	7.18	5.34	10.72	16.58	8.01
	20	8.47	15.35	11.68	28.10	62.03	30.57
	30	12.98	24.09	18.59	53.31	121.19	61.05
	40	17.92	32.66	25.33	109.22	170.33	107.21
	50	22.95	41.49	32.32	139.02	257.50	137.15
	60	27.91	50.24	39.23	170.14	409.80	190.52
	70	33.80	58.78	45.94	234.13	665.25	270.79
	80	38.82	67.83	53.16	303.04	786.67	341.97
	90	44.58	79.39	60.48	383.18	1,138.33	446.29
	100	49.88	88.80	67.65	470.06	1,426.20	586.79
	125	65.87	113.81	85.54	1,054.03	1,871.89	830.88
	150	80.05	137.45	103.77	1,516.72	2,246.27	1,205.21
	175	96.80	160.50	121.10	1,769.51	2,620.64	1,589.25
	200	111.19	183.52	138.52	2,022.30	2,995.02	1,908.28

5.2.3 Percentage of NPV Derived From Carbon

Tables 5-2 and 5-3 can be used to determine the percentage of total NPV derived from carbon value. The results are presented in table 5-4. Due to declining carbon values in the horizontal baseline, the percentage of NPV made up by carbon value is peculiar and does not adequately account for the percentage of NPV derived from carbon values because the NPV of carbon declines as carbon prices rise. The proportion of NPV derived from carbon value, from a BAU baseline, in all scenarios increases as the price of carbon goes up. The forest carbon incentive account results in the highest percentage of NPV derived from carbon, followed by the total carbon incentive account. Percentage results range between 0-13% when incentives are placed on forest carbon, 0-10% when incentives are placed on total carbon and 0-9% when incentives are placed on above ground carbon only. When regulations are relaxed, a higher portion of NPV is derived from carbon. Percentage results range between 0-66% when incentives are placed on forest carbon, 0-65% when incentives are placed on above ground carbon only and 0-64% when incentives are placed on total carbon. The absolute highest proportion of NPV derived from carbon values is obtained when incentives are place on the forest carbon pools. This is expected as the removal of regulations allows the firm with the most flexibility in responding to carbon incentives. Forest carbon account also provides the more incentive to sequester carbon than the other accounts. This is both because of the inclusion of additional carbon pools and the exclusion of forest products. The inclusion of forest products results in a lesser amount of carbon sequestered than when they are excluded because the transfer of carbon from the forest to forest products is not complete as only 85% of forest carbon is transferred to forest products (Kurz *et al.* 1992).

Table 5-4 Percentage of NPV Derived From Carbon

		Restricted			Unrestricted		
	Carbon Price $/t	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
NPV of Carbon Determined by Horizontal Baseline (millions)	0	0%	0%	0%	0%	0%	0%
	1	0%	0%	0%	0%	0%	0%
	2	-1%	0%	0%	-1%	0%	0%
	4	-2%	-1%	1%	-1%	-1%	1%
	6	-2%	-1%	1%	-2%	-1%	1%
	8	-3%	-2%	2%	-2%	-1%	2%
	10	-4%	-2%	2%	-3%	-1%	2%
	20	-8%	-5%	4%	-5%	0%	5%
	30	-14%	-7%	7%	-7%	2%	8%
	40	-19%	-10%	9%	-7%	3%	12%
	50	-26%	-13%	10%	-8%	7%	15%
	60	-34%	-16%	12%	-10%	16%	18%
	70	-43%	-19%	14%	-9%	30%	23%
	80	-54%	-22%	15%	-7%	34%	27%
	90	-67%	-26%	17%	-4%	50%	32%
	100	-83%	-30%	18%	0%	60%	38%
	125	-149%	-42%	21%	42%	65%	45%
	150	-319%	-57%	24%	63%	65%	55%
	175	-1732%	-77%	27%	63%	66%	62%
	200	743%	-105%	29%	64%	66%	65%
NPV of Carbon Determined by BAU Baseline (Millions)	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	1%	0%	0%
	0%	1%	0%	1%	1%	0%	0%
	0%	1%	0%	1%	1%	1%	0%
	1%	1%	1%	2%	4%	2%	1%
	1%	2%	2%	4%	8%	4%	1%
	2%	3%	2%	8%	11%	7%	2%
	2%	4%	3%	9%	16%	9%	2%
	2%	4%	3%	11%	24%	12%	2%
	3%	5%	4%	15%	37%	17%	3%
	3%	6%	4%	19%	40%	21%	3%
	4%	6%	5%	23%	54%	26%	4%
	4%	7%	6%	27%	62%	33%	4%
	5%	9%	7%	53%	65%	41%	5%
	6%	10%	8%	65%	66%	52%	6%
	8%	12%	9%	65%	66%	61%	8%
	9%	13%	10%	65%	66%	64%	9%

NPVs tend to be largest when prices are highest, when regulatory regimes are relaxed and when the lowest possible baseline is adopted, in this case a BAU baseline. Once a baseline is established in this model and we assume that a firm has entered a contract, there is no difference in behavior because the baseline is fixed and hence the value of credits and debits implied by the baseline is fixed. It is important to note that if NPV decreases with carbon price, as it does under a horizontal baseline, a firm would not likely enter into the contract. More specifically, a firm would not enter into the contract if the baseline was horizontal. However if a firm entered a contract under a horizontal baseline then the behavior is the same whether the firm faces a horizontal baseline or whether it faces a declining one because incentives at the margin are identical. Given the nature of Canada's forests and it's history of natural disturbances, it is thought that the most relevant baseline is BAU and therefore is the only case discussed in the remainder of this study. It is important to note that a natural disturbance baseline (typically declining) accents the value of carbon and therefore produces results of the same nature as a BAU baseline although it is a baseline that is not explicitly discussed.

5.3 Carbon Supply, Timber supply and Regeneration Results of Restricted Model Configurations (Scenarios 3 to 5)

The following section presents the carbon supply, timber supply and regeneration intensity results for scenarios 3 to 5, the models with the restricted regulatory regimes. While the influence of the regulatory regimes is pointed out in the following discussion, the examination of the effect of the carbon accounting stance is the primary objective of this section. A discussion of carbon supply when incentives are placed on forest carbon is included (Scenario 4). This is followed by a discussion of timber supply and optimal harvest and regeneration prescription results for scenario 4. A comparison of the carbon

supply of scenario 4 to two additional scenarios (scenario 3: above ground carbon and scenario 5: total carbon) is then presented to isolate the effects of the carbon accounting stance.

The comparison of scenarios 3, 4 and 5 examines the response to different carbon accounting stances in terms of two supply responses. The first is total carbon supplied by the firm and the second is in terms of total carbon supplied. Supply of carbon credits is the amount of carbon supplied relative to the carbon accounting stance and total carbon supply is the carbon supplied in all carbon pools. [20] To determine the carbon supply, either credits supplied or total carbon supplied, carbon stocks for each carbon accounting stance are compared with the appropriate baseline. For example, to determine the credits supplied when incentives are placed on forest carbon, one must compare the carbon stocks in all of the forest carbon pools and compare it to the carbon stocks in all of the forest carbon pools of the BAU scenario.

It is important to note the difference between total carbon supplied and carbon credits supplied, as they are not necessarily the same. For example, carbon credits supplied by the above ground carbon accounting stance are generated by carbon in the above ground pools relative to the above ground carbon BAU. At the same time, there exists a total carbon supply which is the carbon contained in all carbon pools (in this case soil carbon, below ground carbon and carbon contained in forest products) regardless of whether they are included in the carbon incentive account.

[20] Examining total carbon supply helps to determine the effect of placing carbon incentives on the various forest carbon pools.

5.3.1 Carbon Supply for Scenario 4

The carbon credit supply curve generated in period 1 and 2 under scenario 4 is depicted in figure 5-3. The carbon supply of scenario 4 is elastic for carbon prices of $0/t to $4/t. The supply becomes inelastic at carbon prices greater than $4/t. The shape of the carbon supply is governed by four factors which are (i) timber harvest levels including area and supply, (ii) harvest species emphasis, (iii) regeneration prescriptions and (iv) timber regulation constraints.

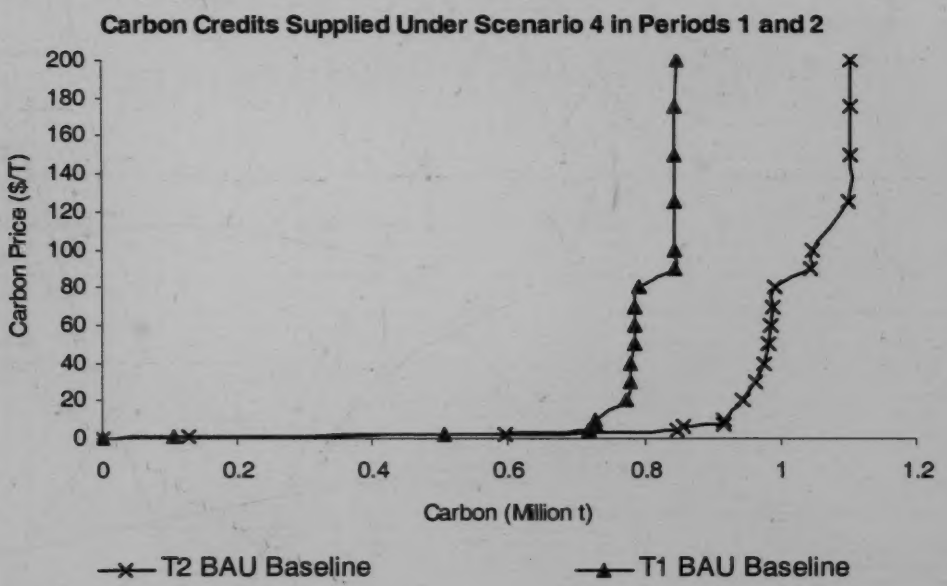


Figure 5-3 'Quasi' Carbon Supply Curves for the First Two Periods With Incentives on Forest Carbon

The elastic portion of the supply curve can be attributed to a reduction in harvest level. This reduction is illustrated in figures 5-4 and 5-5. Figure 5-5 also shows that there are no changes in regeneration practices. The inelastic portion of the supply curve is generated by the lack of flexibility created by the harvest level constraint. This portion of the curve is generated when the model begins to 'bump' against even-flow levels.

Changes in carbon credit supply (as illustrated in the figure 5-3) are mostly generated as a result of changes in harvest emphasis along this portion of the supply curve although, it is important to note that changes in carbon supply can also be generated by changes in the species composition of the forest.

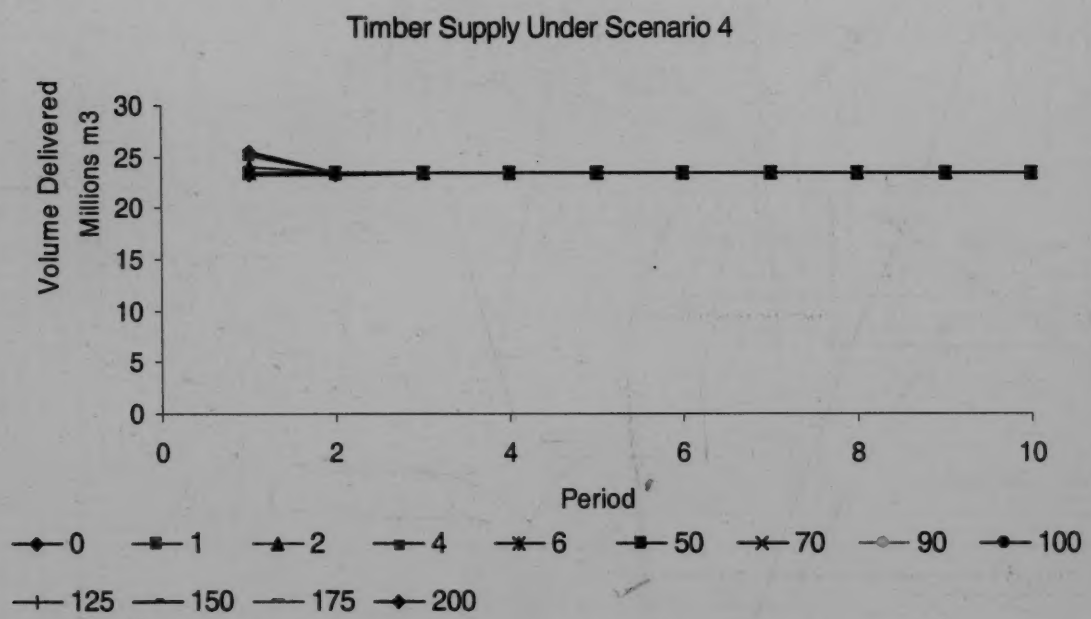


Figure 5-4 Timber Supply Under Restricted Forest Carbon Account

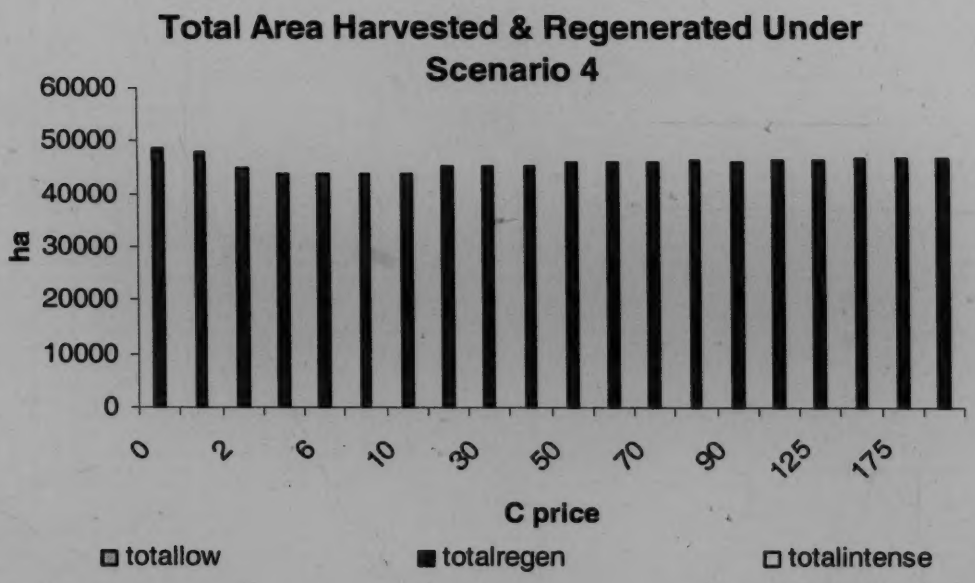


Figure 5-5 Area Harvested and Regenerated under Restricted Forest Carbon Account

5.3.2 Comparison of Carbon Supply Under Different Carbon accounting stances (Scenarios 3, 4 and 5)

The following is a comparison of carbon supply under the three different carbon accounting stances. The effects of placing incentives on different configurations of carbon accounts are examined by again considering total carbon supplied and carbon credits supplied. Also included is a discussion of total carbon stocks and an explanation of carbon supply changes.

It is important to examine the carbon supply under different carbon accounting stances for 3 reasons. The first is that under an above ground scenario, there is lower credit potential because only a fraction of carbon stock is above ground (see figure 2-2). The second is that while there are differing amounts of credits generated by using various accounting configurations there are still impacts on overall carbon stocks. It is therefore

important to examine the effectiveness of using easily measurable above ground carbon as an incentive for altering total carbon stocks. Finally, it is important to consider the effects of including forest products in the incentive stance as NPV results presented in section 5.1 suggest that it may be attractive to firms.

Figure 5-6 illustrates the carbon contained in all carbon pools (total carbon) obtained under the 3 carbon accounting stances. This figure helps to illustrate the effect of placing carbon incentives on various forest carbon pools. Firstly it is important to note that placing incentives on forest carbon results in the highest total forest carbon stocks. The second highest total carbon stocks is obtained when incentives are place on total carbon levels, the lowest total carbon stocks are obtained when incentives are placed on above ground carbon. It is also important to note that while price does effect the total carbon stock levels when incentives are placed on forest carbon and above ground carbon, it has little effect on total carbon stock levels when incentives are placed on total carbon stocks. While figure 5-6 illustrates the total carbon stocks it is important to discussion the supply of carbon or carbon relative to a baseline.

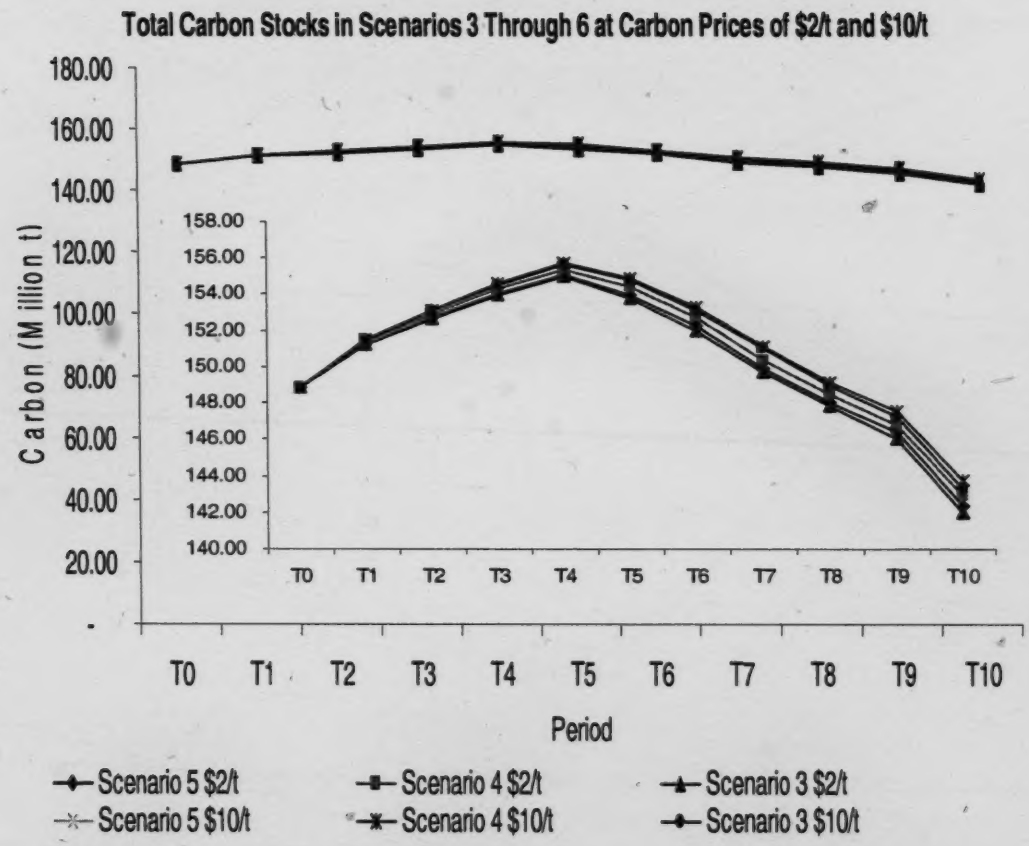


Figure 5-6 Total Carbon Stocks of Restricted Scenarios at Carbon Prices of $2/t and $10/t

Figure 5-7 illustrates the carbon credits supplied in scenarios 3 through 5 from a BAU baseline. In period 1, the most carbon credits are supplied under scenario 4. Scenario 3 supplies the second most carbon credits and scenario 5 supplies the least amount of carbon credits. It is expected that the above ground carbon incentive account will supply minimal carbon credits because there isn't much carbon stored in above ground biomass. The inclusion of forest products generates less carbon than the forest carbon scenario or above ground scenario because including forest products creates an incentive to harvest more as it reduces the penalty for harvest. In this model, the penalty associated with harvesting is not reduced to the greatest potential because forest product

allocation (in terms of what products are produced) is not very flexible in this model as the model does not allow for very much change in lumber: pulp ratios. In the second period, the most carbon credits are supplied again by scenario 4. The second most carbon credits are generated by scenario 5 and the least amount of carbon credits are generated by scenario 3 (although at carbon prices of $175 and $200/t, scenario 3 generates more credits than scenario 5). The nature of carbon credit supply is similar to that discussed in the previous section. The carbon credit supply curves are inelastic due to regulatory constraints and therefore, carbon prices have little effect on the firms ability to generate carbon credits. Figure 5-7 again suggests that at low carbon prices (less than $4/t), there is very little difference in carbon supply between the three incentive accounts and therefore it may not be necessary to provide incentives on forest carbon and total forest carbon to generate credits.

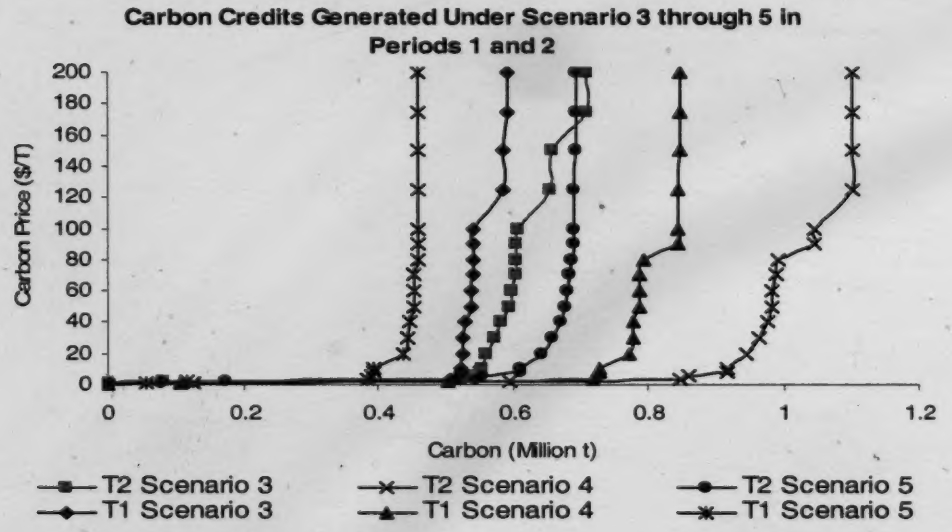


Figure 5-7 Carbon Credits Supplied By Forest Carbon From a BAU Baseline Under Scenario 3 Through 5 in Periods 1 and 2 at Carbon Prices of 1$/t and 2$/t

Figure 5-8 illustrates the total carbon supplied under scenarios 3 through 5 in periods 1 and 2. It is important to examine this case to determine the effect of placing carbon incentives on the various forest carbon pools. In period 1, carbon supply under the forest carbon and total carbon accounting stances are almost identical from carbon prices ranging from $0/t to $80/t. When carbon prices are greater than $80/t, the forest carbon accounting stance generates more carbon than the total carbon accounting stance. At carbon prices smaller than $100/t, the above ground carbon account generates the least amount of carbon. When carbon prices are greater than $125/t, the above ground carbon account generates more carbon than the total carbon account. This implies that at low prices the placement of incentives on carbon pools does affect the carbon present in the forest significantly.

Examination of the results in period 2 produces similar findings. The forest carbon account and the total carbon account are almost identical at $80/t, at prices greater than $90/t, the forest carbon account becomes larger. The above ground carbon account generates the least amount of carbon when carbon prices are less than $100/t, however, when carbon prices reach values greater than $125/t, the above ground carbon account generates more carbon than the total carbon account. The nature of carbon supply is similar to that discussed in the previous section. The carbon supply curves are inelastic due to regulatory constraints and therefore, carbon prices have little effect on the firms ability to generate carbon credits. The changes in carbon supplied by the three scenarios are due to the tradeoffs between storing carbon in the forest and storing it in forest products.

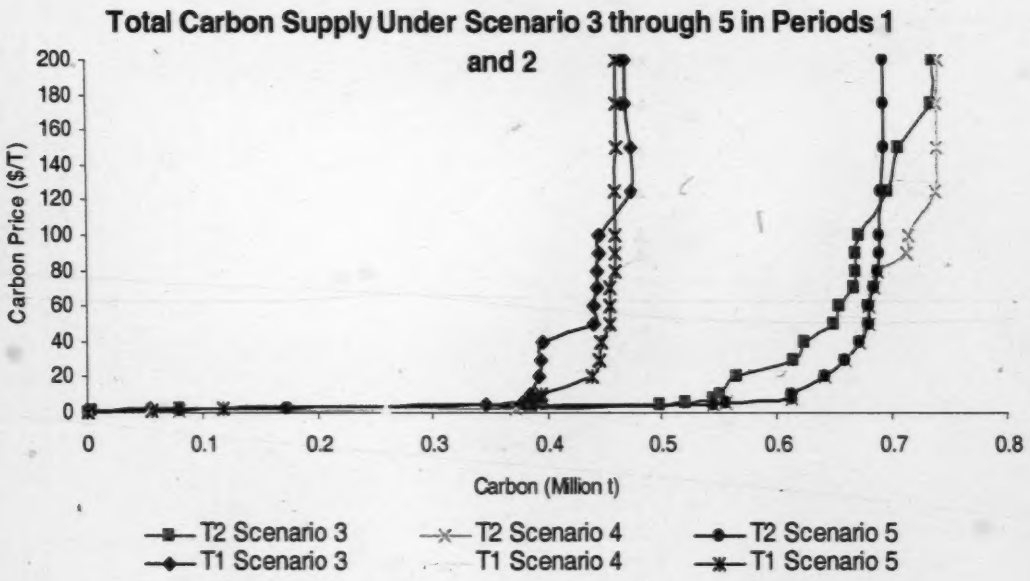


Figure 5-8 Total Carbon Supplied Under Scenario 3 Through 5 in Periods 1 and 2

Figure 5-8 illustrates three important findings; the first is that placing incentives on additional carbon pools may result in an increase in carbon stored in the forest. This can be seen via the difference between the above ground and forest carbon supply curves. Secondly, this figures shows that placing incentives on forest products will not result in additional carbon being stored in the forest as can be seen as the difference between the forest carbon supply curve and the total carbon supply curve. Finally, figure 5-7 suggests that at carbon prices less than $4/t, supply doesn't change drastically across the carbon accounting stances and that placing incentives on purely above ground carbon may be sufficient to generate carbon supply. When carbon prices are greater than $4/t, the addition of carbon pools to an incentive account may result in additional carbon being supplied.

Scenarios 3 through 5 best represent the regulatory structure faced by forest product firms currently operating in Alberta. The results of the regulated scenarios presented in this section suggest that a forest product firm may be able to generate carbon credits for the purpose of selling. The number of carbon credits generated however is greatly dependent both upon the baseline and the carbon account configurations. At low carbon prices the three incentive stances appear to generate carbon supplies that are roughly equal to each other.

5.4 Effects of Regulatory Regime on Carbon Supply

The following section provides a discussion of the effects of the regulatory regime on carbon supply. The section begins with a discussion of total carbon stocks in the unregulated scenarios and a comparison to the regulated scenarios. This is followed by a comparison of carbon credits supplied by forest carbon in a regulated (scenario 4) and unregulated (scenario 7) scenario. This is followed by a discussion of why the carbon credit supply differs under the two scenarios. Finally, a brief comparison of scenarios 3 to scenario 6 and of scenario 5 to scenario 8 is included.

Figure 5-9 illustrates the total carbon stocks of the unrestricted scenarios (scenarios 6 through 8) under the three carbon accounting stances at two carbon prices ($2/t and $10/t). This figures shows that the highest levels of total carbon are generated when incentives are placed on forest carbon. The second highest levels of carbon stocks are generated when incentives are placed on total carbon, and the least amount of carbon is generated when incentives are placed on above ground biomass only. This figure also illustrates that at low carbon prices ($2/t) total carbon stocks decline over time. At higher

carbon prices ($10/t) carbon stocks increase over time. The increase in carbon stocks over time observed at higher carbon prices can be attributed to changes in harvest levels, discussed later in this section.

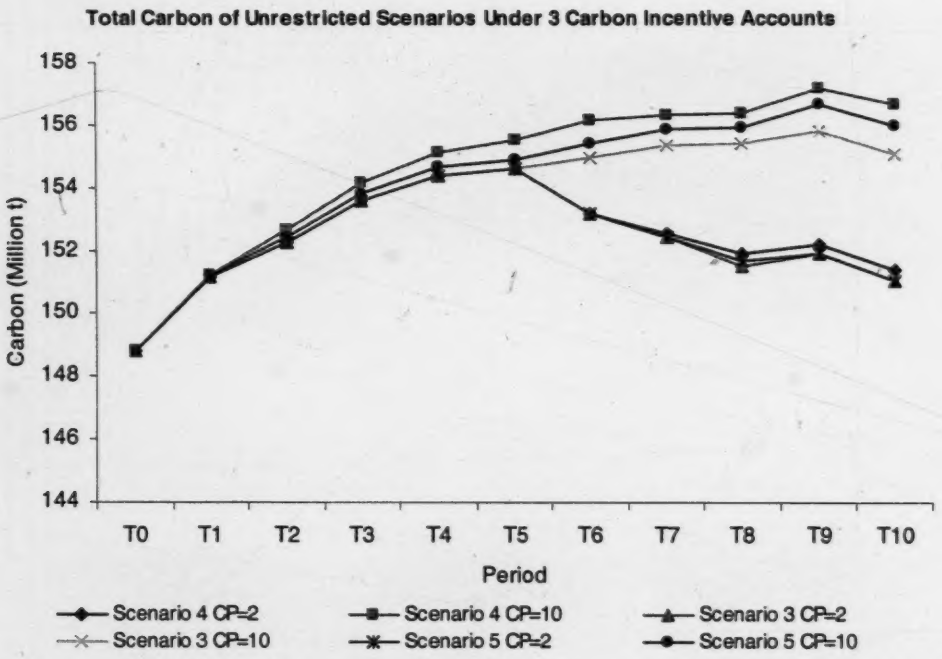


Figure 5-9 Total Carbon Stocks of Unrestricted Scenarios Under 3 Carbon accounting stances

Figure 5-10 illustrates the total carbon stocks in scenarios 4 and 7 at two carbon prices ($2/t and $10/t). This figure illustrates the effects of regulations on total carbon stocks present in the forest (and product pools) . The relaxation of regulations results in higher total carbon stocks then when regulations are enforced. A discussion of the differences between the regulated scenarios and unregulated scenarios is included below.

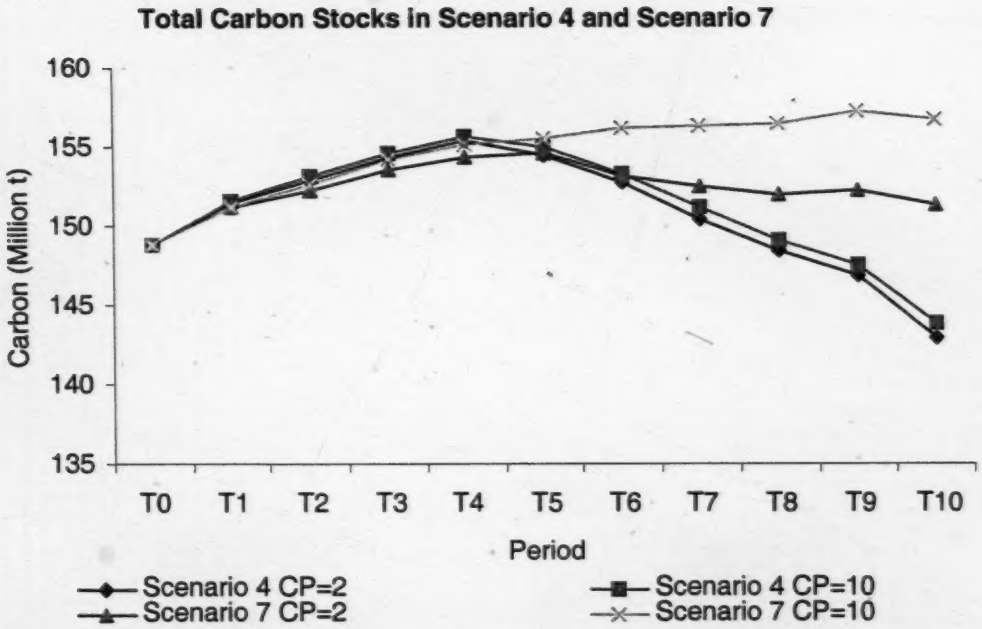


Figure 5-10 Total Carbon Stocks in Restricted and Unrestricted Forest Carbon accounting stances

Figure 5-11 illustrates the carbon credits supplied under scenarios 4 and 7 in periods 1 and 2. The figure shows that in both periods, the carbon credit supply under scenario 4 is inelastic and unable to provide large quantities of carbon at any price. When restrictions are removed (scenario 7), larger quantities of credits are supplied as the firm is better able to respond to carbon price increases. An examination of timber supply and area harvested and regenerated can again provide an explanation for the differing carbon storage.

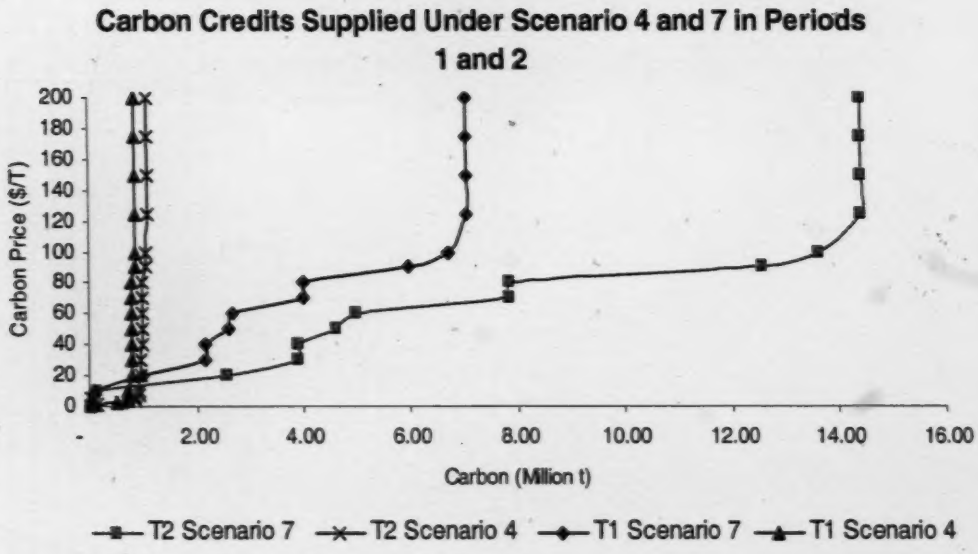


Figure 5-11 Carbon Supplied Under Restricted and Unrestricted Forest Carbon Accounts in Periods 1 and 2

Figure 5-12 illustrates the maximum timber supply (0 $/t) and the minimum timber supply (200 $/t) in scenario 7 (unregulated) as well as the range of timber supply obtained from scenario 4 (regulated). An examination of the figure shows that imposing even-flow regulations results in a stable timber supply due to regulatory constraints. Figure 5-12, shows that relaxing regulatory constraints results in a significantly reduced timber supply. As carbon prices increase, timber supplied under this account decreases, and at sufficiently high carbon prices (i.e. $200/t), timber supply is minimal. The decrease in harvest levels reflects the decision that it is better to store carbon in the living tree and forgo profits that could be earned as a result of harvesting.

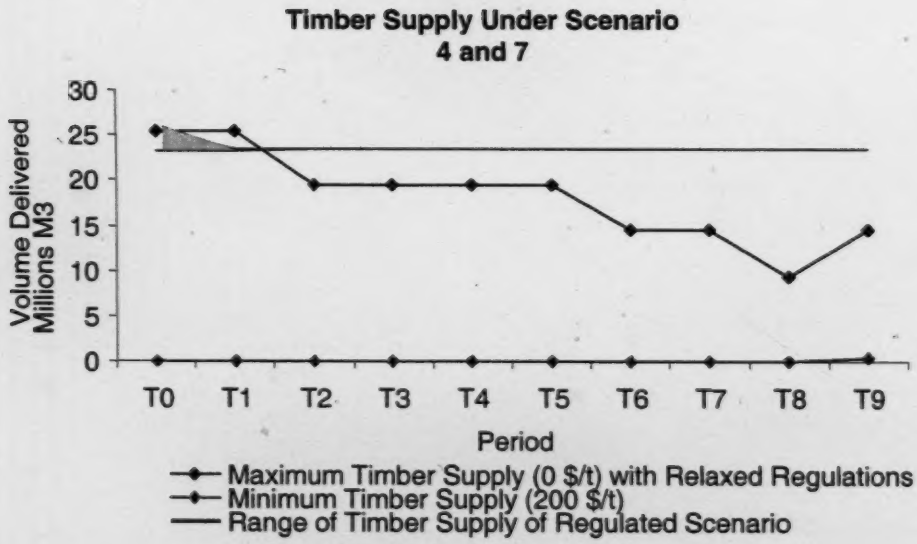


Figure 5-12 Timber Supply Under Restricted and Unrestricted Forest Carbon Account

Figure 5-13 illustrates the total area harvested and regenerated under scenarios 4 and 7. The figure shows the constant harvest levels and basic regeneration (current practices) observed in scenario 4. The figure also illustrates the change in regeneration practices that occur in an unregulated scenario (scenario 7) and illustrates that harvest levels decline as carbon prices increase. At low carbon prices, regeneration is carried out by the extensive method however at higher carbon prices (greater than $40/t), there is an increase in basic forest management in the unregulated scenario to increase carbon stocks. This is contrary to the regulated scenario, which shows basic management as a means of maintaining timber supply to satisfy regulations. At extreme carbon prices (i.e. $200/t) there is no regeneration in scenario 7 as harvest levels have dropped to zero (see figure 5-12).

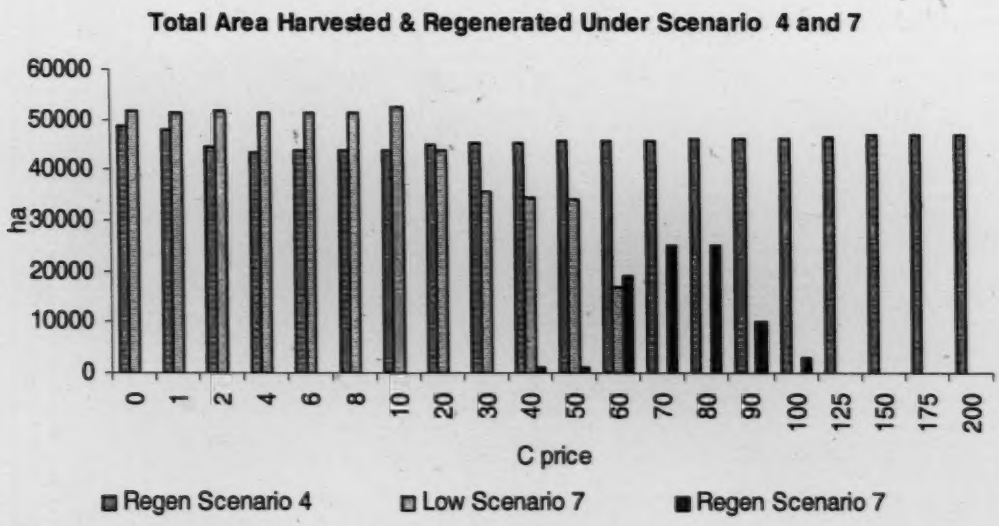


Figure 5-13 Total Area Harvested and Regenerated by Restricted and Unrestricted Forest Carbon accounting stances

The following is a brief comparison of scenario 3 to scenario 6 and scenario 5 to scenario 8. Figure 5-14 provides an illustration of carbon credits supplied in periods 1 and 2 by scenarios 3 and 6. Figure 5-15 provides an illustration of carbon credits supplied in periods 1 and 2 by scenarios 5 and 8. Both of these figures have a similar shape to the results presented in figure 5-12, where the regulated scenario is inelastic in its supply of carbon and the un-regulated scenarios not. For brevity, a brief explanation of the results is included although not depicted through figures. In all cases, the un-regulated scenarios are able to supply larger quantities of carbon than their regulated counterpart. This is expected, as the un-regulated scenarios are able to decrease their timber supply in a similar manner as presented in figure 5-12. The results presented in figure 5-13 are also similar to the trend in area harvested and regenerated in scenarios 5 and 8.

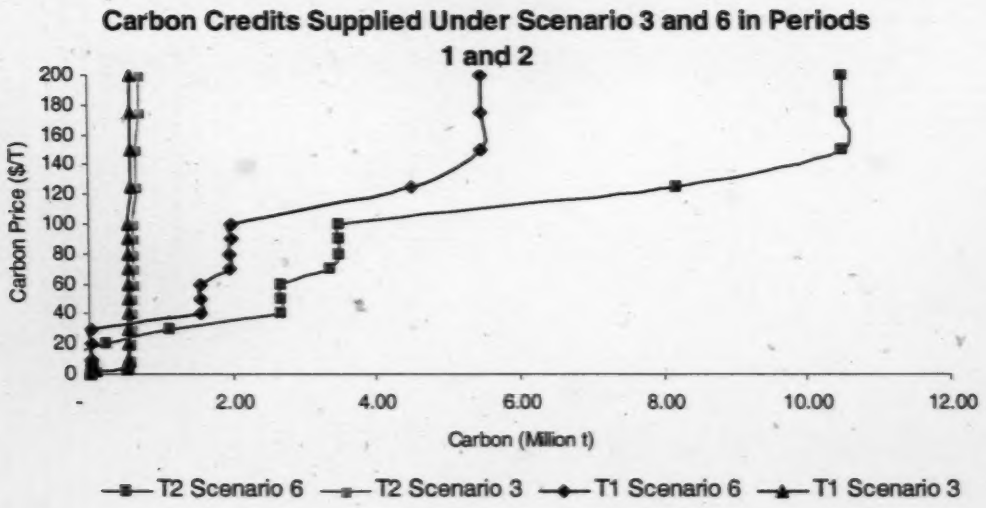


Figure 5-14 Carbon Supplied Under Scenario 3 and 6 in Periods 1 and 2

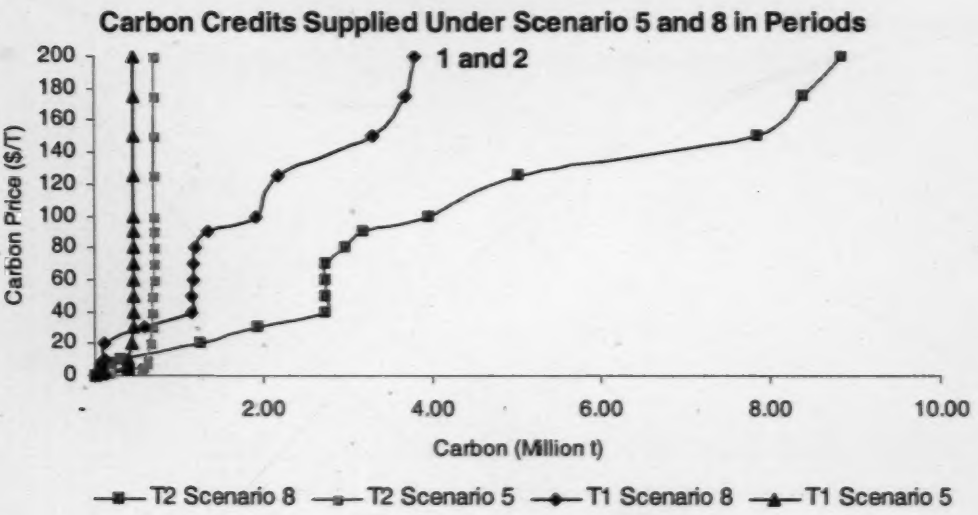


Figure 5-15 Carbon Supplied Under Scenario 5 and 8 in Periods 1 and 2

5.5 Summary

Chapter 5 examined optimal forest management for different carbon prices, baselines, carbon accounting stance and regulatory structures on forest management. A

discussion of NPV, carbon supply curves and carbon credit supply curves is included to determine how carbon incentives affect the optimal management of the forest. The results presented and discussed in Chapter 5 illustrate four important points. The first conclusion is that baselines have a significant effect of the NPV of forest and timber benefits. A second conclusion is reached by analyzing the effects of carbon prices and showed that in the long run low carbon prices fail to generate significant carbon credits while higher carbon values make investments in silviculture more attractive and thereby generate more carbon credits. In the short run, reducing harvest and changing harvest emphasis generates carbon credits. A third conclusion reached is that the carbon accounting stance can have an impact on the magnitude of carbon credits generated (as illustrated in figure 5-8). The most carbon credits are generated by an account stance that includes forest carbon only (excluding forest products). It is important to note that a complete carbon account (all carbon pools including forest products) did not necessarily result in the most carbon credits generated. A discussion of total carbon supplied versus total carbon credits supplied was also included in this chapter and illustrated that using different carbon accounting stances had little impact on total carbon supplied. A final conclusion reached is that the regulatory environment, such as even-flow constraints, has a significant impact on and severely limits the generation of carbon credits via forest management as illustrated in figure 5-11.

Given the current regulatory structure, it is unknown if a firm would enter into a carbon credit trade. The many uncertainties surrounding baselines, carbon accounting stances and regulatory constraints may make it difficult to enter a long-term contract.

However, given the right baseline, carbon price and relaxed regulatory constraints, a forest products firm may be able to generate sufficient carbon credits and may wish to enter into a carbon trade with a buyer seeking offsets. Given that it may be possible for a firm to enter into a contract to generate carbon credits it is important to discuss the policy implications of the results. Chapter 6 provides a discussion of the policy implications of the results presented in Chapter 5 including a discussion of the model limitations and the need for future research.

Chapter 6: Conclusions and Areas of Future Research

This study provides an analysis of optimal forest management when a firm is faced with various incentives to sequester carbon. Carbon supply curves were developed for various carbon accounting stances and regulatory regimes. Supply curves were analyzed to determine the source of carbon supply by examining timber supply and harvest/regeneration decisions. These timber supply and harvest/regeneration decisions can be used to examine how baselines, incentive structures and regulations affect forest management. This analysis can be used to examine the issues surrounding whether Canada should invoke Article 3.4 of the Kyoto Protocol. An analysis of the two baselines, three carbon accounting stances and two alternative regulatory structures included in this study suggests that Canada's forests could play a role in climate change mitigation policy if certain conditions are satisfied. If Canada is to use article 3.4, this analysis suggests two important conditions must be met. The first is that a downward sloping baseline is critical given disturbance rates in Canada's forests. The second is that forest regulations must be relaxed to allow for reductions in harvest levels.

When regulations are imposed NPV for the firm obtained from an objective function that maximizes both timber values and carbon values (equation 3.1) relative to a BAU baseline, increases when carbon prices increase for all scenarios (as seen in table 5-2). When regulations are relaxed, the NPV increases relative to when regulations are imposed. It is these scenarios (BAU baseline with relaxed regulations) that produce the highest NPVs. When NPVs are calculated relative to a horizontal baseline, values decline for above ground and forest carbon incentives. The inclusion of forest products

results in an increasing NPV relative a horizontal baseline. When regulatory constraints are relaxed, all incentive packages result in increasing NPV relative to a horizontal baseline. This implies that carbon supply would be zero for baselines that result in declining NPV's and firms would not enter into carbon contracts. However, given the right baseline, carbon accounting stance and carbon price a firm may enter into a deal to sequester forest carbon credits.

An examination of NPV of carbon (table 5-3) and percentage of NPV derived from carbon values (table 5-4) shows that higher carbon prices result in a higher percentage of value being obtained from carbon benefits in both the regulated and unregulated scenarios. Table 5-3 can also be used to illustrate the effects of carbon incentives under different incentive accounts on forest management. Using the knowledge that higher NPV's represent more carbon being stored, it is possible to examine the effects of a carbon accounting stance. From a BAU baseline, the most carbon is stored by the forest carbon account in the regulated scenarios. In the unregulated scenario the most carbon is again stored by the forest carbon account. More carbon is stored in the unregulated scenarios than the regulated scenarios. These results are illustrated by figures 5-8, 5-14, and 5-15. Carbon supply in un-regulated scenarios is due to decreases in timber supply that occur as carbon prices increase. However decreases in timber supply are limited by regulations under restricted scenarios. These results illustrate the choice between storing carbon on the stump and storing it in forest products. Given the choice, a firm would choose to store carbon in the forest rather than forest products because it is more profitable to do so (refer to table 5-2). Given the

tradeoffs between storing carbon on the stump and storing it in forest products, namely an increase in carbon is mostly the result of a decrease in timber supply, it important to examine the results presented in terms of their implications for policy.

6.1 Policy Implications

Many of the results presented in Chapter 5 have various policy implications. The following is a discussion of the policy implications of the results and assumptions presented in chapter 5.

This study considered a wide range of carbon prices and therefore it is important to discuss the implications of the carbon prices modeled. Each scenario was modeled for carbon prices ranging from $1/t to $200/t however current carbon prices (given in US dollars) range between US$1/t and US$1.50/t and it is expected that carbon prices will range between US$3/t and US$5/t during 2003-2007 and by the first commitment period be around US$5/t and US$8/t (Boone, 2002). Therefore a discussion of carbon prices up to $200/t may not be applicable at least in the short term. It may be more realistic to examine the effects of carbon prices in the lower range of the values presented in this study and disregard high carbon prices.

The selection of baselines is vital to the success of forest carbon sequestration. Given the process of determining carbon credits, firms will want the lowest possible baseline. For example, a firm would prefer a declining BAU baseline to a horizontal

baseline. Given the nature of Canada's forests, a declining baseline, such as BAU or natural disturbance baseline, may in fact be the most appropriate.

As discussed, the decision of carbon accounting stance can have a large effect on the generation of carbon credits. Incentives placed on purely above ground carbon will result in the generation of the least amount of carbon credits. Incentives placed on all carbon pools (total carbon including forest products) results in the second most carbon credits. The most carbon credits are generated when incentives are placed on all forest carbon pools (excluding forest products) although it is important to note that carbon stocks in these pools may be both difficult and expensive to determine. Therefore the decision of which carbon pools are eligible for trading has a large effect on the number of credits that can be generated even though it has little impact on total carbon supplied.

When discussing which carbon accounting stance is the best configuration, it is also important to discuss the export of Canada's forest products. If forest products are included in the framework, it is important to note that the majority of forest products made in Canada are exported (GERT, 2002). It is therefore uncertain whether carbon credits will remain in Canada or be sold with the forest product. It is important to account for the final destination of forest products to ensure that no double counting is occurring. If products are sold with their credits to a foreign country the value of credit and the associated long-term debits (due to the eventual decay of forest products) will be embedded in the product price thus raising the price of wood products. Alternatively products could be sold without the credits in which case the foreign country just receives

the debits associated with future decay resulting in lower wood prices . A third alternative is that products sold to a foreign country would not result in a transfer of carbon onto the foreign countries account. In that case, it is necessary to make some assumption about how long the product takes to decay and credit is based on the NPV of carbon stored minus carbon decaying.

It is also important to consider the effects of regulations on the firm's ability to react to market incentives because regulations greatly reduce the amount of carbon credits that can be generated. The current regulatory regime significantly reduces the firms ability to change management practices in response to market incentives. The effects of regulations can be illustrated by examining the difference between credits generated in a regulated and un-regulated industry as illustrated in figure 5-11.

The effects of carbon accounting stances and regulatory constraints may cause the Federal Government to invest more time into analysis of carbon accounting stances as well as negotiations regarding what a carbon accounting stance will look like. In order to fully support and encourage forest carbon sequestration it may be necessary to relax even flow regulations thus greatly increasing the potential amount of carbon credits generated. In addition, the Provincial Governments may wish to re-examine current regulations placed on the forest industry.

Two additional factors, both relating to regulatory structure, may affect the ability of forest product firms to generate carbon credits. Accounting for the forests ability to

sequester carbon in the decision to harvest results in the optimal decision of delaying harvest although current regulations limit the ability of firms to do so. This is consistent with the single stand rotation work of Sedjo (1999), Englin and Callaway, (1993) and (1995), Plantinga and Birdsey (1994). The first limitation relates to the political ability to reduce harvest levels. In order to effectively generate carbon credits by controlling forests harvest, levels must decline substantially. The feasibility of reductions of such magnitude in the current policy framework and political economy is questionable. Due to current regulations, it is not possible to significantly reduce harvest levels in an effort to generate carbon credits. If even-flow regulations were lifted and harvest levels were allowed to decline, the result might be mill closures and possibly loss of jobs. It is important to note that the results likely over estimate responses in the short run because firm's costs of processing will increase if harvest rates decrease due to large capital stocks. The ability to shut down mills in an effort to generate carbon credits is therefore questionable. The second factor affecting the ability of forest product firms to store carbon is related to the ownership of carbon. The current regulatory structure creates incentives to harvest wood and not store it on the stump even though it may be optimal to do so. The decision to delay harvest is further complicated because while firms have rights to the wood on crown land, the rights are highly constrained by regulation. For example, un-used AAC could be reallocated by its owner (the Crown) to another firm. The scope of ownership right to timber standing on crown land in addition to the ownership of carbon stocks is therefore a major issue.

While carbon credits can be generated in the long run by practicing intensive management (but not in the short run), the usefulness of these credits is somewhat questionable. There is uncertainty surrounding how long carbon markets will be needed as forest carbon is often seen as a means of buying time to allow for the development of technology. Therefore as technology is developed, the usefulness of forest carbon credits generated in the future is questionable.

One final political implication is the nature of BAU baselines. The declining baselines presented suggest that forests may be a liability if brought into the current framework for satisfying emission reductions. If carbon stocks are declining, Canada may choose to not invoke article 3.4 of the Kyoto Protocol and may choose to meet international commitments by another means.

6.2 Limitations

One of the limitations of this model is that carbon prices are assumed constant over time. Currently carbon credits supplied exceeds demand although in the future carbon prices will likely rise as supply is exhausted and regulations become stricter (Boone, 2002). Future research could include making carbon price a function of time. Another limitation is associated with the assumption of a constant disturbance rate. Future research could incorporate stochastic disturbances and evaluate the risks associated with and the effects of climate change. One additional limitation of this research is that only three carbon accounting stances were modeled. The possibility of other carbon accounting stances exist, such as a configuration that accounted for above ground carbon and forest products. There is also the potential to expand the definition of

forest carbon to include other carbon pools in the forest such as the vast amounts of carbon stored in peatlands. One final limitation of this research is that only two baselines were modeled however there exists the potential for additional baselines and therefore they should be examined. One potential baseline that should be examined given the nature of Canada's forests is a natural disturbance baseline, which is likely declining.

6.3 Summary

Despite the limitations presented above, the study identifies some essential information for the Federal Government in the formulation of policy for carbon sequestration in Canada's forests. The study identifies the importance of regulations on the generation of carbon credits. It also identifies the importance of baselines and carbon accounting stance in determining carbon supply and credits. This study provides the Federal Government with information that will prove useful in determining whether to invoke article 3.4 of the Kyoto Protocol as well as information that may be useful in future negotiations regarding forest carbon as a means of achieving emission reduction targets. Canada may wish to invoke article 3.4 if they are able to negotiate three conditions which may better enable it's forests to make a valuable contribution and include: (i) a declining baseline, and (ii) relaxation of even-flow regulations.

Literature Cited

Adams D., R. Alig, B. McCarl, J. Callaway and S. Winnett. 1999. Minimum Cost Strategies for Sequestering Carbon in Forests. Land Economics, August 65(5): 360-374.

Adams, R., D. Adams, J. Callaway, C. Chang, and B. McCarl. 1993. Sequestering carbon on agricultural land: Social cost and impacts on timber markets. Contemporary Policy Issues 11(1):76-87.

Alig, R., D. Adams, B. McCarl, J. Callaway and S. Winnett. 1999. Assessing Effects of Mitigation Strategies for Global Climate Change with an Intertemporal Model of the U.S. Forest and Agriculture Sectors. Environmental and Resource Economics (9): 259-274.

Alig, R., D. Adams and B. McCarl. 1997. Ecological and Economic Impacts of Forest Policies: Interactions Across Forestry and Agriculture. Ecological Economics (27): 63-78.

Apps, M., W. Kurz, S. Beukema and J. Bhatti. 1999. Carbon Budget of the Canadian Forest Product Sector. Environmental Science and Policy (2): 25-41.

Armiro, B.D., M. Flannigan, B. Stocks and B. Wotton. 2002. Perspectives on Carbon Emissions from Canadian Forest Fires. The Forestry Chronicle Vol. 78. No. 3: 388-340.

Boone, Corrine. 2002. *Personal Communications.*

Climate Change Central. 2002. Reduction and Removal of Agricultural Greenhouse Gas Emissions in Alberta: Soil Measuring, Monitoring and Verification Land Use Database and Benchmark Field Plan. Calgary, AB.

Englin, J. and J. Callaway. 1993. Global Climate Change and Optimal Forest Management. Natural Resource Modeling 7(3): 191-202.

Englin, J. and J. Callaway. 1995. Environmental Impacts of Sequestering Carbon Through Forestation. Climatic Change 31: 67-78.

GERT, 2002. Greenhouse Gas Emissions Reduction Trading Pilot (GERT) Final Report: GERT Technical Committee.

Griss, Paul. 2002. Forest Carbon Management in Canada: Final Report of the Pollution Probe Forest Carbon Management Workshop Series. Calgary, AB.

Hauer, G., T. Williamson, M. Renner. 2001. Socioeconomic impacts and adaptive responses to climate change: a Canadian forest sector perspective. NRCan, CFS, Northern Forestry Centre, Edmonton, Alta. Inf. Rep. NOR-X-373. 55 p.

Hoen, H., and B. Solberg. 1994. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. Forest Science 40, 429-451.

Kurz, W., M. Apps, T. Webb and P. McNamee. The Carbon Budget of the Canadian Forest Sector: Phase 1. Edmonton, AB: Forestry Canada, 1992.

Kurz, W.A., S. Beukema, and M. Apps. 1999. Estimation of Root Biomass Dynamics for the Carbon Budget Model of the Canadian Forest Sector. Canadian Journal of Forest Resources 26: 1973-1979.

Lougheed, Hugh. 2000. *Personal Communications.*

Natural Resources Canada. (1999) National Climate Change Process Forest Sector Table Options Report: Options for the Forest Sector to Contribute to Canada's National Implementation Strategy for the Kyoto Protocol. Ottawa, ON.

Nilsson, S. and W. Schopfhauser. 1995. The carbon-sequestration potential of a global afforestation program. Climatic-Change 30(3) 267-293.

Plantinga, A., and R. Birdsey. 1994. Optimal Forest Stand Management When Benefits Are Derived From Carbon. Natural Resource Modelling Volume 8 (4), Fall: 373-387.

Price, D., H. Halliwell, M. Apps, W. Kurz and S. Curry. 1997. Comprehensive Assessment of Carbon Stocks and Fluxes in a Boreal-Cordilleran Forest Management Unit. Canadian Journal of Forest Research 27: 2005-2016.

SBSTA, 2000. UNFCC - SBSTA, 2000. Proposals Related to Kyoto Protocol Articles 3.3 and 3.4. Paper Number 3. Section 2. http://unfccc.int/resource/docs/2000/sbsta/misc06.htm

Singh, T. 1981. Biomass Equations for Ten Major Tree Species of the Prairie Provinces. Environ. Can., Can. For. Serv., North. For. Res. Cent. Edmonton, Alberta. Inf. Rep. NOR-X-242.

Sedjo, R. 1999. The potential of high-yield plantation forestry for meeting timber needs. New Forests 17:339-359.

Sedjo R., B. Sohngen and R. Mendelsohn. 2001. Estimating Carbon Supply Curves for Global Forests and Other Land Uses. Resources for the Future. Discussion Paper 01-19. 31 p. Washington, DC.

Sohngen, B and R. Haynes. 1997. The Potential for Increasing Carbon Storage in United States Unreserved Timberlands by Reducing Forest Fire Frequency: An Economic and Ecological Assessment. Climate Change 35(2): 179-197.

van Kooten, C. 1995. Climate Change and Canada's Boreal Forest: Socio-economic Issues and Implications for Land Use. Canadian Journal of Agricultural Economics 43: 133-148.

van Kooten, C., C. Brinkley and G. Delcourt. 1995. Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. American Journal of Agricultural Economics 77 (May): 365-374.

van Kooten, C., E. Krcmar-Nozic., B. Steenes and R. van Gorkom. 1999. Economics of fossil fuel substitution and wood product sinks when trees are planted to sequester carbon on agricultural lands in western Canada. Canadian Journal of Forest Research 29: (1669-1678).

Weldwood. 2000. 1999 Forest Management Plan: Volume II Resource Analysis. Hinton, Alberta.

Williams, D. 1994. What are the key influences on timber supply? Timber supply in Canada: Challenges and choices. Conference proceedings, Kananaskis, Alberta, Nov. 16-18, 1994. Ottawa, Natural Resources Canada. pp.53-58.

Woodrising Consulting Inc. 1999. An Estimation of the Impact of Net Carbon Sequestration of Forest Management Including Wood Product Storage. (Prepared for Sinks and Forest Sector Tables). May.

Age Class Distribution: North

Yield Strata	AW	OH		MC		PI			SB	XX Total	Total
site class	M	M	F	M	G	F	M	G	M		
age class											
1	58.94	1312.54	749.27	9709.88	363.86	692.60	18814.50	699.68	1123.59	97.53	33622.38
2	62.63	311.81	185.72	4655.63	302.85	295.39	6651.34	498.41	316.26	0.00	13280.04
3	138.33	1282.72	1923.63	5847.42	2246.82	1665.21	4421.00	1981.57	522.47	0.00	20029.19
4	3256.34	3437.45	2615.90	5602.12	3122.88	1335.86	4941.29	3993.49	1363.79	0.00	29669.11
5	348.23	802.32	1057.85	1269.87	649.80	3406.34	1558.61	120.68	830.32	0.00	10044.03
6	292.40	548.71	295.74	992.45	418.30	31.00	509.02	33.17	502.37	0.00	3623.17
7	729.65	1243.93	696.97	4042.72	630.61	504.27	2235.82	207.94	845.11	0.00	11137.03
8	1703.33	1705.77	1525.96	3759.83	675.18	717.76	1908.25	688.19	1379.88	0.00	14064.14
9	1883.41	1352.75	1791.31	4337.38	327.21	3224.19	5119.38	499.27	767.15	0.00	19302.06
10	5176.89	3277.28	2554.11	3734.32	1253.36	1907.33	7550.44	2860.54	1311.32	0.00	29625.58
11	12161.47	9148.11	12455.48	15025.66	7028.09	7283.33	25041.85	7885.12	5569.03	0.00	101598.13
12	6227.13	4920.21	9079.24	9915.11	5329.77	4045.39	12279.87	4170.82	6482.52	0.00	62450.05
13	885.10	1977.82	2115.43	4619.37	3148.39	520.83	2566.84	974.78	2531.96	0.00	19340.53
14	1838.71	2545.76	3000.56	7024.96	2459.10	905.42	2140.54	834.78	2067.43	0.00	22817.26
15	35.63	73.99	825.19	1064.18	164.36	839.05	138.86	12.56	552.24	0.00	3706.05
16	33.21	80.14	893.45	532.52	32.45	1071.74	295.44	2.97	432.63	0.00	3374.55
17	498.92	958.46	1668.16	3232.55	442.31	725.78	743.33	88.64	804.15	0.00	9162.30
18	0.00	3.32	130.04	106.79	50.81	90.43	26.20	2.46	33.64	0.00	443.69
19	0.00	12.07	162.72	115.83	43.39	260.23	4.16	0.00	24.49	0.00	622.89
20	110.68	168.96	5769.98	2011.38	184.06	3448.88	890.27	1.44	435.89	0.00	13021.53
21	0.00	0.00	219.97	67.18	0.00	77.87	18.37	0.37	33.03	0.00	416.80
22	0.00	0.00	89.74	0.16	0.00	39.51	0.00	0.00	5.89	0.00	135.30
23	0.00	0.00	185.96	0.00	0.00	105.08	0.00	0.00	36.49	0.00	327.53
24	0.00	0.00	255.62	0.00	0.00	14.73	0.00	0.00	10.55	0.00	280.89
25	0.00	0.29	653.25	84.35	0.00	153.78	16.60	0.00	6.83	0.00	915.11

Age Class Distribution: South

Yield Strata	AW	OH		MC			PI		SB	XX Total	Total
site class	M	M	F	M	G	F	M	G	M		
age class											
1	62.05	617.17	589.99	4894.48	200.97	564.60	9471.22	534.60	856.77	16.75	17808.60
2	1.29	182.48	83.03	2423.79	204.54	113.59	6858.43	364.38	39.20	0.00	10270.72
3	60.76	533.37	1274.48	3962.06	958.96	1748.83	3751.56	2589.98	437.05	0.00	15317.05
4	602.96	1257.65	886.52	2506.03	817.34	1561.16	2974.56	997.81	404.39	0.00	12008.41
5	559.82	1064.03	276.24	1642.00	683.52	1880.17	2571.14	467.82	217.08	0.00	9361.82
6	167.78	195.91	174.49	591.24	264.64	727.72	1706.80	155.44	522.41	0.00	4506.43
7	656.45	806.13	1168.12	1931.96	396.16	1850.51	4440.60	373.92	835.58	0.00	12459.42
8	985.75	853.76	1776.98	4066.19	300.88	1635.73	3416.88	1362.98	1472.14	0.00	15871.30
9	974.44	807.98	1449.31	2669.73	306.71	1757.03	2312.62	325.60	972.83	0.00	11576.26
10	1452.52	1451.66	2775.46	3766.76	723.59	7296.66	12712.52	1789.14	1450.53	0.00	33418.84
11	4557.74	3221.56	7508.83	9973.32	3384.18	7091.50	16951.88	5229.49	5173.12	0.00	63091.62
12	1010.00	1023.46	6327.73	6513.24	1301.88	4363.23	10881.90	3070.34	2801.12	0.00	37292.91
13	546.65	613.27	1303.91	2370.65	532.26	596.56	1523.27	822.59	1124.88	0.00	9434.04
14	656.15	530.41	3936.94	3438.22	1028.36	538.76	1439.53	1436.04	1925.76	0.00	14930.17
15	31.38	87.22	924.95	351.06	74.12	81.18	252.25	126.76	239.32	0.00	2168.23
16	142.54	65.90	1414.61	264.71	14.35	155.81	270.32	7.73	210.17	0.00	2546.13
17	174.47	174.24	2648.31	1505.58	65.66	374.91	643.49	43.55	460.18	0.00	6090.39
18	0.00	13.39	787.08	299.42	1.30	23.65	89.34	11.92	81.41	0.00	1307.53
19	0.00	20.34	812.22	426.15	12.86	62.79	93.48	0.00	124.68	0.00	1552.51
20	16.70	170.85	3790.16	883.62	10.48	239.76	87.05	11.83	456.34	0.00	5666.80
21	0.00	30.25	65.22	213.84	0.00	0.18	34.58	0.00	22.66	0.00	366.73
22	0.00	0.00	554.71	57.88	0.00	3.13	11.93	0.00	58.15	0.00	685.79
23	0.00	0.00	364.04	34.29	0.21	0.00	0.00	0.00	0.00	0.00	398.54
24	0.00	0.00	16.09	10.77	4.22	0.00	0.00	0.00	0.00	0.00	31.09
25	0.00	0.00	89.16	43.69	0.00	1.34	2.79	0.00	6.52	0.00	143.50